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METALLOGENETIC ZONES.

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ONE of the most important problems of metallogenesis at the present day is that of the existence of a definite arrangement in space of the ore deposits of metalliferous regions. In many localities it is known that some sequence exists in the minerals of economic value. There are several instances where the general character of the ores of a particular mine or of a whole region have been found to undergo changes in depth, and in other instances lateral variations can be traced either along the courses of single lodes or in the metal content of all the lodes when followed in certain directions. There are thus many isolated facts available, but hitherto few attempts have been made to generalize from them, or to build up a coherent account of the whole subject. It may be doubted whether at the present time sufficient data are yet available, and the investigation is attended with peculiar difficulties of a practical nature, since frequently when the product of a mine or of a mining field undergoes a marked change in any given direction, work forthwith stops in that direction. However, there are cases, and important cases, where continued exploitation of changed ores has been economically possible and these have yielded evidence of much value. The best known of these in Britain is perhaps the mining field of Cornwall, where copper in the upper levels in many mines gave place to tin in depth and the latter has been mined for many years with success-

ful results. Other examples will appear in the course of this discussion.

The practical bearing of this subject is obvious and does not need elaboration. It is clear that it would be of value to a mining geologist if he were able to predict with a reasonable amount of certainty changes in the character of ore likely to be encountered in the deeper levels of a mine, or to form an opinion as to the probable horizontal extent of a run of ore. This problem is, however, not quite of the same nature as that involved in the study of ore shoots in the ordinary sense of the word. This last expression involves the idea of variations in the concentration of ore of constant qualitative composition, whereas the point now under consideration is rather a vertical or lateral variation in the mineralogical character and metal content of the deposits, an alteration in the *kind* of metal rather than in the *quantity* of metal.

It is evident that in a problem of this kind there are many factors to be taken into account, since the possible causes of variation are numerous. In the first place it is necessary to eliminate here all the features connected with oxidation and secondary enrichment of primary ores; although this is the simplest and best known cause of ore zones, it is not the subject now under discussion. What we are here concerned with are variations in the character of *primary* ores, a much more fundamental matter. Sometimes, however, the two sets of phenomena may be somewhat difficult to disentangle; account must always be taken of the simple fact that primary and secondary ore zones are not necessarily parallel, although they may be so. Secondary ore zones must conform more or less accurately to the contour of the country as existing at the time of their formation, and their depth and general disposition depends largely on the ground-water relations of the district. The primary zones on the other hand have no necessary relation to the land surface either at the time of their formation or at any other time, and may undergo any amount of geological disturbance by tilting or otherwise at any time after their formation. They are likewise entirely dependent on the cause to which they owe their formation, whatever this

may be. In a great number of cases primary ore zones can be shown to be genetically related to igneous activity, especially to the intrusion of plutonic batholiths and laccoliths. Such zones are obviously for the most part to be found in the types of ore deposits occurring as veins and lodes, which often have great vertical and horizontal extent; hence they are more likely to exist in connection with acid intrusions. The limited and localized character of the ore deposits of the basic plutonic rocks does not favor their development, except perhaps on a very small scale.

Although as above stated there is frequently to be observed a change in the metals present in ores in depth in any one vein, nevertheless this is by no means universal, and there are many cases of persistence to great depths. One of the most striking is the Morro Velho Mine in Brazil, belonging to the St. John del Rey Co. This is now the deepest mine in the world, having reached in 1917 a vertical depth of 6,126 feet below the surface. The ore body is a vertical vein of lenticular cross section, pitching at 45°, and has a maximum thickness of about 30 feet. All reports on the mine agree in the remarkable fact that there is no material change in the tenor of the ore at the greatest depth yet reached. The ore body consists of a mixed gangue of quartz, chalybite, dolomite and calcite, with pyrite, pyrrhotite, arsenopyrite and a little chalcopyrite. Most of the gold is in the arsenopyrite and free gold is rare. The great gold reefs of Mysore, India, are also now worked to a depth of about 6,000 feet. These are certainly extreme cases, but other instances could be quoted in which ores have persisted, without change, to great depths. More common, however, are instances in which the amount of payable ore, or rather more correctly where the tenor of the ore, falls off in depth, without much change in its character. Investors in mines are only too well acquainted with this phenomenon, and it is hardly necessary to particularize further on a somewhat painful subject.

To most British mining geologists the best known case of a definite change in the chief ore production of a large district is that of Western Cornwall. A hundred years ago most of the

lode mining in Cornwall was copper mining, and the chief product of many mines that still exist was copper ore, tin taking quite a subsidiary place, especially in the Camborne-Redruth area. As time went on, however, and the mines became deeper, copper gradually gave place to tin, and the production of the former metal is now negligible in quantity. Such mines as Dolcoath, East Pool, and South Crofty are now regarded simply as tin mines, with tungsten and arsenic as subsidiary products. The numerous abandoned shallow mines of this area were mainly copper mines and when the supply of this metal fell off in depth, most of them were closed down. The distribution of the two metals in this area is obviously in close connection with the form of the granite masses. These take the form of bosses and cupolas, probably connected at no great depth, and forming the upper portions of a great batholith; the junctions of the granite and slate are as a rule fairly steep. Since the metalliferous zones are apparently on the whole parallel to these junctions, they are necessarily oblique to the present surface and probably follow in depth, approximately at any rate, the undulations of the granite-slate contact. Nevertheless, it is possible that the richer mineralization is confined to the neighborhood of the domes and cupolas, and is less developed where the junction lies originally deeper. The rich tin zone lies partly within the granite and partly in the slate, but the greater part of the copper-bearing portion of the lodes lies in the slate. Near the upper levels of the tin zone is a sub-zone of wolfram, and arsenopyrite is also abundant here. In the upper part of the copper zone, zinc, lead, silver and other metals begin to come in. It must be borne in mind that this brief statement is highly generalized and many local exceptions could doubtless be brought forward, but in the main the sequence holds, and the general succession of ores can be shown diagrammatically as in Fig. 22.

Besides the lodes running parallel to the granite-slate contact, often called the *Champion Lodes,* there are others having a general direction nearly at right angles to them, called *Cross Courses;* these are demonstrably newer than the former set and some of

them are faults, displacing the main lodes. Some of the cross courses, especially at a considerable distance from the granite contact, contain ores of lead and zinc, and still further away are some large iron lodes, mainly siderite where not oxidized. Hence

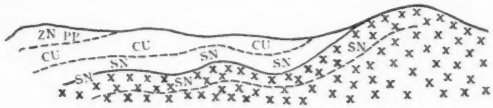

FIG. 22. Generalized section through the Camborne District showing relation of ore zones to granite-slate contact.

it appears that the general succession in Cornwall from below upwards may be generalized as tin, tungsten, copper, zinc, lead, iron.[1] Whether anything lies below the tin is not known, but it is unlikely; the tin content of the lodes at the deepest level yet reached in the New Shaft of Dolcoath shows a distinct falling off, and appears to be unpayable below about 3,000 feet from the surface.

In one respect this is a particularly easy case to deal with, since the space relations of the different types are simple and well known. Only two rock types here exist in any large amount, granite and slate. The greenstones and elvans (quartz porphyries) are hardly present in sufficient quantity to affect the general question, although they certainly do cause local variations and interruptions of lodes. Both granite and slate are well-defined and homogeneous masses, arranged on a simple plan, and both apparently favorable to lode-formation. We are not here confronted with a complication such as occurs in the Shelve district in Shropshire, where the metalliferous veins are strictly confined to one type of coarse-grained sediment, the Mytton Grits, and die out at the margin of the overlying and finer-grained Hope Shales.[2] The suitability of the country rock for vein-formation

[1] Davison, "The Primary Zones of Cornish Lodes," *Geol. Mag.*, vol. LVIII., 1921, pp. 505–512.

[2] Special Reports on the Mineral Resources of Great Britain, vol. XXIII., "Lead and Zinc Ores in the Pre-Carboniferous Rocks of West Shropshire and North Wales," by B. Smith and H. Dewey, *Mem. Geol. Survey*, 1921.

is a factor of considerable importance in a question of this sort. It is quite within the bounds of chemical theory that from a mixed solution of metallic compounds one or more might be precipitated on passing through a rock of a particular composition, leaving others in solution. In such a case the ore zone would have to conform to the extent of the precipitating rock. This may, in some instances, be the origin of ore shoots. Apart from this, however, is the simple fact that different metals may be deposited from solution at different temperatures in a homogeneous rock without the interference of actual chemical reactions, such deposition being purely a physical process. In the case of mineralization due to intrusion this would naturally lead to successive zones concentric to the intrusion, in conformity with the distribution of the isotherms. But here again there are various complications to be taken into account, one of which is the time factor. In most instances we have no guarantee that, to put it in simple language, all the metals started from the intrusion at the same time. If they did so, the matter is simple; the metals should be deposited in zones around the intrusion according to the temperature at which they became insoluble in the carrying solutions. In discussions of this subject it is generally assumed, either consciously or unconsciously, that ore deposition takes place during the *cooling* of the rocks, but in the case of veins in sediments at any rate this is by no means necessarily the case. As is well known rocks are bad conductors of heat, and the temperature of the whole region around the intrusion may actually rise by conduction after the arrival of the mineralizing solutions. In many instances also it is clear from field evidence that earth movements have taken place during deposition, veins have been reopened and often brecciated, and then partly or wholly filled up again and again by deposition of similar or different ore minerals, sometimes apparently at long subsequent periods. In some instances also there may have been more than one period of mineralization owing to different intrusive phases in the same region. Hence the whole problem is evidently very complex.

Let us, however, consider briefly from the theoretical point of

view an ideal case, simplified as much as possible. The conditions assumed are the intrusion of a metalliferous igneous rock, granite for instance, into a series of homogeneous stratified rocks of a character favorable to lode-formation, that is, capable of allowing the formation of open fissures under stress. The metallic compounds are to be supposed to concentrate in the last residue of the cooling magma as vapors or solutions with water and other more or less volatile substances; that is to say, pneumatolysis is at any rate not excluded, though not essential to the argument. During cooling, jointing is developed in the granite and the dynamic force of the intrusion gives rise to planes of fracture in the surrounding rocks, usually parallel or at right angles to the contact. The latter class may be continuous with similar fissures in the granite itself. Along these fissures the ore-bearing solutions pass outwards from the granite, often altering and mineralizing the walls of the fissures themselves, both in the granite and in the sediments. From the center of the granite outwards there must be a gradual decrease of temperature, and there may be an abrupt change of gradient at the contact, though it is unlikely that this will be very marked, at any rate in the later stages of cooling. Thus the solution, travelling outwards, will eventually come to a region where it is no longer in equilibrium and will begin to deposit one or more of its components in the solid form. If the solution is a complex one, the point of supersaturation for the different components will be reached at different temperatures, or what comes to the same thing, at different distances from the point of departure. This in the simplest case must necessarily lead to a zonary arrangement of the solid products of crystallization, and the metals will be deposited in the inverse order of their solubility in the complex magmatic solution. Here, however, a further point of importance arises. The solubility of any one metal in the solution will be affected by the presence of all the other metals and the presence of an additional one may vary the normal order of the others. An example will make this clearer. Let us suppose that in one case three metals, *A*, *B*, *C*, are present and are deposited in that order. In another instance there are

four metals, *A, B, C, D.* Here the presence of *D* may modify the relative solubilities of *A, B, C,* so that they may be deposited in a different order, such as *B, A, C,* or *A, C, B;* furthermore the additional metal may come in any position in the series either in space or in time, according to its own solubility in the presence of the other three. Thus it is evidently difficult to predict the behavior of a given case on the basis of data derived from other cases. Empirical observation alone can afford sure ground, until sufficient experimental facts have been accumulated to cover every case. On physicochemical grounds, however, it seems safe to assume that the same assemblage of metals under similar conditions will be deposited in the same order.

It certainly is a fact that in some groups of metals a definite order in space is well known to exist. For example, a comparison of a great number of reports on silver-lead-zinc mines shows that commonly in depth zinc increases at the expense of lead and often entirely replaces it, while silver is more abundant in the upper levels of the lead zone. It has already been mentioned that in Cornwall lead and zinc occur further from the granites than copper, and it is an interesting and important subject of inquiry whether there is any evidence of the occurrence of an important zone of copper ores below the lead-zinc veins of the north of England. As to this point there is actually some evidence. It is well known that copper ores occur in small quantities in many localities in the Carboniferous limestone and an interesting case is that of the once famous Ecton Mine on the borders of Staffordshire and Derbyshire. This mine has apparently been forgotten by the present generation of writers on mining geology, but affords some useful lessons. The following description is taken from Phillips and Louis:[3]

> The principal deposit, which as early as the year 1778 had been worked to a depth of 200 fathoms, is a pipe-vein, piercing the highly contorted limestone beds almost vertically. There are eight main lodes coursing E. and W., and the same number of N. and S. veins, together with many smaller branches. The upper portions of the lodes contain lead, poor in

[3] "Ore Deposits," 1896, p. 284.

silver, and blende with copper ores, the latter predominating in the lower levels. The principal ores are chalcopyrite and erubescite, and with these occur oxides and carbonates. . . . The veins sometimes attain a great thickness; being in one case as much as seventy yards from side to side.

This mine in 40 years yielded copper to the value of £670,000 and the ore is stated to have as a rule contained about 15 per cent. of copper. Although the account here quoted is not very clear as to the relations of the "lodes" to the "pipe vein," one thing is quite definite, namely that the copper was more abundant in depth in this, for the period, unusually deep mine.

As regards this question, there is another consideration that may be of assistance. In the Lower Paleozoic rocks of Central and North Wales, the Lake District and the Southern Uplands of Scotland are many metalliferous veins, often rich, containing in varying proportions lead, zinc, and copper, with silver and occasionally other metals, such as the arsenic, tungsten, and molybdenum of the Carrock Fell area in Cumberland. An admirable series of Memoirs descriptive of the Lead-Zinc Ores of the British Isles is now in course of publication by the Geological Survey, in which full details of all known occurrences will be found. In innumerable instances it is clearly shown that on the whole the richest zinc deposits are at lower levels than the richest lead deposits, and silver increases in quantity in the upper part of the lead zone. The time relations of these veins to those of the Carboniferous limestone, as well as the exact date of formation of the latter, are unknown. It is clear, however, that some are at least post-Triassic, since lead is found in the Dolomitic Conglomerate of the Mendips and lead and copper in the Keuper sandstone of Alderley Edge, Cheshire, while copper ores occur in the Peckforton Hills and at various other points in Cheshire and Shropshire. All these presumably belong to a late phase of the Armorican crust movements.

It is quite clear that on the whole copper is more abundant in the veins in the Lower Paleozoic rocks in the localities before mentioned than in those of the Carboniferous limestone, and the suggestion at once arises that the Lower Paleozoic veins may

represent the lower zones of veins once existing, whose upper portions were similar to those of the Pennine area or of the Carboniferous limestone of Flint and Denbigh, these upper portions having been since removed by denudation.[4] It might be suggested that the veins in the Lower Paleozoic rocks were related to the Caledonian earth movements and intrusions and at first sight this view might appear more probable, but Finlayson,[5] in his admirable discussion of the whole subject, has brought forward evidence to show that, with the probable exception of Anglesey, all of these are related to the Armorican movements. Why Anglesey is excepted is not quite clear. It may be suggested therefore that if the lead-zinc veins of the Carboniferous could be followed down into the underlying Lower Paleozoic rocks of the Pennine area, in all probability a copper zone would be found. This conclusion is admittedly highly speculative, but it may at some future time be worthy of practical investigation. At any rate it is significant that the order in which the ores are here found, namely copper, zinc, lead, from below upwards, is the same as that prevailing in Cornwall.

In many other districts in the British Isles and elsewhere there is evidence that blende is on the whole earlier and deeper than galena. Thus in the Shelve district in Shropshire, Mr. C. T. F. Hall states that blende increases in depth and there is no appreciable quantity of silver in the galena. In Flintshire there are two sets of veins of which the older contain blende, while the later ones have practically no blende.[6] In Wales again blende increases in depth, and many of these veins carry copper, as is also the case in the Isle of Man. Considerable quantities of pyrite are also found in many veins in the Lower Paleozoic rocks.

Among British examples this question has been more completely studied in Cornwall than anywhere else, and no apology is needed for returning once more to this often-mentioned area

[4] Throughout the north of England and North Wales the Devonian system is absent, the Carboniferous resting with a marked unconformity on Silurian and older rocks.

[5] Finlayson, *Quart. Journ. Geol. Soc.*, vol. LXVI., 1910, p. 284.

[6] Hall, "Lead Ores." Imperial Institute Monographs, 1921, pp. 49, 51.

since some work of great importance has lately appeared.[7] From a detailed microscopic study of veinstones Davison has shown that as a general rule, with slight variations, the order of arrival of the minerals in the lodes is as follows:

1. Quartz, mica, tourmaline, topaz, cassiterite, wolfram, stannite, and molybdenite.
2. Quartz, chlorite, fluor, chalcopyrite, mispickel, pyrite and blende.
3. Lead and silver ores.

Wolfram is often earlier than cassiterite and the latter is usually before tourmaline. Chalcopyrite is often before mispickel and pyrite is usually later than both.

The following are the chief metalliferous zones recognized in ascending order, which is equivalent to an order of decreasing age.

4. Silver, lead, and zinc minerals.
3. Dominant copper.
2. Tin and copper in fair proportions.
1. Dominant tin.

The ores of Zone 4 often occupy fissures belonging to a later series of earth movements, but the other three can all be seen in the same lodes. The latter also sometimes carry lead, zinc, and silver in their highest levels along with some copper. In the neighborhood of ridges or cupolas in the granite copper is often replaced by wolfram, and there is then a wolfram zone just above or just inside the granite. The zones run approximately parallel to the granite-slate contact, which is undulating in depth, patches of metamorphosed slate being seen at the surface in places far from any visible granite outcrop. As a rule the base of the copper zone nearly coincides with the contact.

Cronshaw has also investigated many typical lodes in great detail and has drawn up the following scheme showing the relative ages of the different minerals, the newest being at the top.

[7] E. H. Davison, *Geol. Mag.*, vol. LVIII., 1921, pp. 505–512.

H. B. Cronshaw, *Bull. Inst. Min. Met.*, No. 204, 1921, with discussion and author's reply in subsequent numbers.

10. Calcite.
9. Pyrite, hematite and chalybite, with quartz and fluorspar.
8. Galena, blende and chalcopyrite, with quartz and fluorspar.
7. Chalcopyrite, with quartz and fluorspar, accessory tourmaline, chlorite and cassiterite.
6. Chlorite, with accessory tourmaline, cassiterite, mispickel, quartz and fluorspar.
5. Fluorspar, with accessory tourmaline, cassiterite, mispickel, quartz and chlorite.
4. Blue tourmaline and cassiterite, with mispickel and accessory quartz and fluorspar.
3. Brown tourmaline, with accessory quartz.
2. Quartz and cassiterite, with tourmaline and mispickel.
1. Quartz, with wolfram, mispickel and felspar and local developments of tourmaline, cassiterite and topaz.

Of these groups, numbers 2 to 6 correspond to Davsion's tin zone, group 7 to his copper zone and group 8 to his lead-zinc-silver zone. Group 9 is the iron lodes, such as the great Perran lode near Perranporth. The calcite deposits may be of quite different origin, and much later.

From the data here given the following further generalization is drawn, the mineralization being divided into periods corresponding to the order of arrival of the different constituents.

Stages.	Gangue.	Ore.		
10	Calcite.	Iron ores.		
8, 9	Quartz.	Zinc-blende, galena.		
7		Chalcopyrite.		
6	Chlorite.	Cassiterite.	Mispickel.	Wolfram, chalcopyrite.
5	Fluorspar.			
3, 4	Tourmaline.			
1, 2	Quartz.			

It will be observed that quartz comes at two very distinct periods, while cassiterite and mispickel cover a long range; they both reach a maximum in stages 3 and 4.

From the above summaries it is clear that in Cornwall there is a close correlation between distribution in space, and order in time of the different minerals, both ore and gangue, the later

minerals being the more distant from their source in the granite. The correlation between the schemes as set forth by Davison and Cronshaw and the primary zones of Spurr [8] is clear and need not be discussed in detail at this point.

In this connection it is of interest to note that, as pointed out by Emmons,[9] a zonary distribution can sometimes be recognized in the types of rock-alteration that accompany the formation of ore deposits. Thus Emmons says "in many metalliferous districts three principal types of alteration are recognized, chloritic alteration in a zone extending far out from the deposits, extensive sericitization within this zone and silication near the master fractures. Where the fractures are closely spaced the area of sericitic alteration may be hundreds of feet wide and the chloritic alteration may extend over thousands of feet." This generalization refers chiefly to the types of alteration brought about by the great copper-bearing acid batholiths of western America, but similar ideas are applicable in many other regions. In Cornwall something of the same sort can be observed; thus at Dolcoath, where copper is predominant from the surface to about 900 feet, with tin below, the veinstuff of the upper zone is mainly a green quartz-chlorite rock, while in the deeper zone this is replaced by a blue rock composed of quartz and tourmaline, showing a higher degree of alteration and more far-reaching chemical changes.

In this discussion it has hitherto been assumed, either explicitly or tacitly, that the mineralization is due directly to the intrusion of igneous rocks. Now the argument is capable of application in another way, in the converse sense. If it is regarded as established that a definite generalized succession of mineral zones exists, the occurrence or otherwise of this sequence can be applied as a test of the igneous origin of any particular set of ore deposits on a large scale. It is well known, for example, that there has been much discussion as to the primary or secondary origin of certain lead-zinc deposits, especially those of the Pennine area

[8] Spurr, "A Theory of Ore Deposition," Econ. Geol., vol. II., 1907, p. 781.

[9] Emmons, W. H., "The Principles of Economic Geology," New York, 1918, p. 248.

in England and of the Mississippi Valley in America. It is not proposed here to discuss either of these specific cases. They are merely brought forward as examples of the possible application of the method. It is, however, evident that if in any instance there is no zoning at all, or zones occur in an order inconsistent with a general and well-established law, the formation cannot have been due to the causes to which the law is applicable. Further generalizations are obviously needed before this can be considered a workable proposition. Nevertheless the fact remains that if in a large number of areas where the mineralization is known to be of igneous origin the ores occur in a regular order, then, if in any other area the same ores occur in a different order, their formation is in all probability due to a different cause.

We will now proceed to consider from the theoretical point of view and on general grounds some of the problems here presented. It may be assumed as an axiom that in any chemical and physical processes involved in ore-formation the controlling factors are temperature and pressure and that under varying conditions of temperature and pressure the same substances may behave in different ways and form compounds possessing different mineralogical characters, or to put it in a still simpler form, under varying conditions the same *metals* may form different *minerals*.

For the sake of simplicity we will deal first with the case where the mineralization is of igneous origin.

When a mass of heated igneous material is injected into a series of comparatively cool rocks at a considerable depth, the lines of equal pressure will, apart from variations due to small local causes, run approximately parallel to the earth's surface,[10] since the pressure is due simply to the weight of the overlying rocks. On the other hand, the lines of equal temperature, or isotherms, are the resultant of two independent factors. First there is the gradual increase of temperature downwards, which is of universal occurrence, though the rate of increase varies locally;

[10] As a matter of convenience lines of equal pressure will here be called *isobars;* this term is commonly associated with barometric pressure, but there is no etymological or other reason why it should be so limited.

secondly there is the temperature gradient set up by the heated intrusion. If this last was the sole cause, the isotherms would be parallel to the contact surface. But the combination of the two causes must give the isotherms a more complex form, varying with the shape of each individual intrusion. A simple instance is shown diagrammatically in Fig. 23. The isobars and isotherms

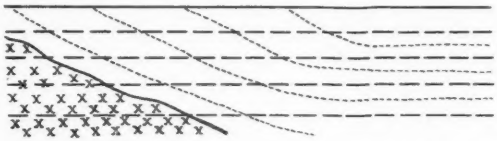

FIG. 23. Isobars and isotherms in relation to an intrusion. Broken lines are isobars, dotted lines isotherms.

therefore cut one another obliquely, marking off regions which may be regarded as the stability fields of certain possible chemical compounds.[11]

In this ideal case the intrusion is assumed to give off a number of different products, *A, B, C*, . . . , which travel outwards to distances controlled by the temperature, and form compounds controlled jointly by temperature and pressure; hence there is evidently much room for variation. The same considerations apply to changes set up in the country rock by the heat of the intrusion. The minerals found at any point are therefore a function of the chemical composition, the temperature and the pressure, and the whole problem is evidently one of great complexity. When we take into account possible original local variations in the composition of the country rock, it becomes still more so, and such cases cannot be profitably considered, at any rate in the present state of our knowledge.

However, taking the simplest possible case and reducing to a purely diagrammatic form, the relations may be expressed as in

[11] Since we are here dealing with a mass in three dimensions we should in strictness always speak of isothermal and isobaric *surfaces*, and the stability fields are in reality solid figures.

Fig. 24. Here A, B, C, D represent the metals given off from the intrusion K; the lines a, b, c, . . . , are the isobars and x, y, z the isotherms here considered for simplicity as straight lines;

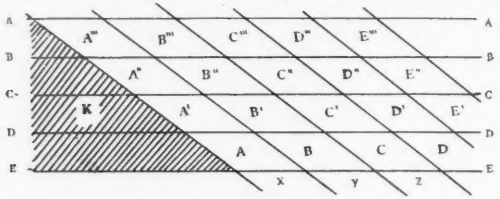

FIG. 24. Diagrammatic representation of stability fields of compounds deposited from an intrusion.

within the spaces bounded by these lines the metals A, B, C will be deposited as modifications A', B', A'', B'' and so forth, with different gangue minerals and different alterations in the country rock. From this diagram it appears that sinkings in any direction will always encounter some kind of change in the character of the ore. Probably the nearest approach that is yet known to this ideal development is to be found in the tin-silver-bismuth mineralization of Bolivia. When such an area has undergone deep denudation, the effects observed will evidently vary according to the direction of the section formed by the ground surface.

CONCLUSION.

The foregoing brief sketch of the generalized distribution of metals as revealed by recent detailed investigations of the principal ore deposits of the British Isles serves to show that so far as our present knowledge goes there is a considerable body of evidence indicating the existence of a definite arrangement in space of metallic compounds in relation to igneous intrusions In Cornwall the relation of the ore bodies to granites is obvious and beyond question and the sequence of metals is definite; in other British areas the existence of large underlying intrusions is hypothetical, but the ores are either clearly related to great orogenic uplift of an anticlinal character as in the Pennine Chain,

or occur in regions of great crustal disturbance, with evidence of abundant hypabyssal and volcanic activity in past times, as in Wales and Shropshire, and furthermore in those cases where the intrusions themselves are not seen, the character of the gangue-minerals, including much fluorspar and barytes, affords additional and confirmatory evidence.

Furthermore it is to be noted that the metallogenetic sequence of Britain, which may be summarized as tin, tungsten, copper, zinc, lead, silver and iron, is on the whole similar to that set forth in America by Spurr, Butler, Lindgren, Billingsley, Grimes, Sales and others during the last few years, and summarized in a recent communication by Professor Kemp in ECONOMIC GEOLOGY. The statement here given is therefore offered for what it is worth as a contribution to the study of this highly interesting subject, a subject which is likewise of the very greatest importance from the practical and economic point of view.

[12] Kemp, J. F., ECON. GEOL., vol. xvi, pp. 474–478.

SEDGWICK MUSEUM,
CAMBRIDGE, ENGLAND.

PRIMARY CHALCOCITE: BRISTOL COPPER MINE, CONNECTICUT.[1]

ALAN M. BATEMAN.

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INTRODUCTION.

In recent years many minerals have come to be considered as indicating rather specific conditions of origin, temperature, and pressure, in the formation of the deposits wihch enclose them. Among such minerals chalcocite occupies a place of more than usual interest. As it is always formed when deposits of copper ores have been subject to the process of secondary enrichment,

[1] Presented before the Ann Arbor Meeting, Society of Economic Geologists, December, 1922.

it is, therefore, usually of secondary or supergene origin, and by some geologists is considered diagnostic of secondary enrichment of ore deposits. On the other hand, a few geologists have maintained—and their arguments have considerable force—that some chalcocite has also been formed as a primary or hypogene mineral and that its occurrence is entirely independent of secondary enrichment. Their contention, however, has not gone undisputed. This marks a swing of the pendulum of thought from supergene to hypogene copper minerals as is at present evident in the case of the silver minerals. If it be true that chalcocite has been formed from both supergene and hypogene solutions, then its presence in an ore deposit cannot be considered as a conclusive indication of secondary enrichment.

In this connection the ore of the old copper mine at Bristol, Connecticut, attracted the writer's attention; the deposit was examined and suites of the ores and rocks were studied under the microscope. The investigation has proved of greater interest than was at first suspected, not only because of the light it may throw on the origin of hypogene chalcocite, but also for the unusual occurrence of ore and the interesting problems raised concerning its origin and deposition. Although the Bristol Mine has been made famous the world over because of its yield of remarkable chalcocite crystals, its period of economic importance has passed long since and the chief interest of the deposit lies in the features mentioned above. The following pages are concerned with the geologic setting of the deposit and the points of ore genesis connected with it.

GENERAL FEATURES.

Location.—The mine lies at an elevation of 350 feet near the northern line of the town of Bristol, Connecticut, and about four miles from its center. It is on the contact between the red Triassic sandstone of the Farmington River Valley and the crystalline rocks of the western upland. The former gives rise to a flattish topography and the latter is bordered by a line of rolling hills, here and there marked by steep faces, which in the vicinity of the mine rise to an elevation of 650 feet.

History.—In the earlier part of the nineteenth century the State of Connecticut boasted of a number of mines, and the Bristol Mine ranked first among the copper properties. It is reported to have been discovered in 1836 and was first described by Shepard in 1837.[2] Mention was also made of it by Percival in 1842.[3]

Prior to 1847 it was worked in a desultory way and there was shipped to England about 125 tons of high-grade ore. From 1847 to 1853 it was more vigorously worked. During this period[4] some half million dollars was spent upon the property; workings were extended to a depth of 240 feet and to a maximum distance of 500 feet along the vein and 120 feet across it. The workings may be seen from the old drawing made by Benjamin Silliman and J. D. Whitney in 1855,[5] here reproduced as Fig. 25. During this same period, nearly $200,000 was obtained from about 2,200 tons of picked ore with an average copper content of 33 per cent. Some time after this the mine was closed. It was again opened in 1888 and a new shaft was sunk in the sandstone to a depth of 378 feet. Levels were run at depths of 30, 40, 50, and 60 fathoms, respectively, each one of which traversed the sandstones lying between the shaft and the contact, and penetrated into the schists. (See Fig. 26.) The mill was rebuilt and considerable mining activity took place until 1895, since which time the property has been idle. There are no data available as to the amount of copper that was produced during this period, but several thousand tons of tailings on the dumps indicate a considerable extraction of ore.

Description of Mine.—The principal opening of the mine is a large pit some 100 feet or so in diameter, which represents a portion of the mine that has caved in. It is now filled by water. Two working shafts are visible. One is 125 feet from the schist-

[2] Shepard, C. U., Report on the Geol. Surv. of Conn., 1837, p. 46.

[3] Percival, James G., Report on the Geology of the State of Conn., 1842, p. 77.

[4] Data from mine records.

[5] *Amer. Jour. Sci.*, vol. 20, 1855, p. 363.

sandstone contact in the sandstone, and is said to be 240 feet deep. The other shaft lies 225 feet further eastward in the sandstone area, and is 378 feet deep (Fig. 26). The former is the one shown in Fig. 25, and the latter would lie to the left of

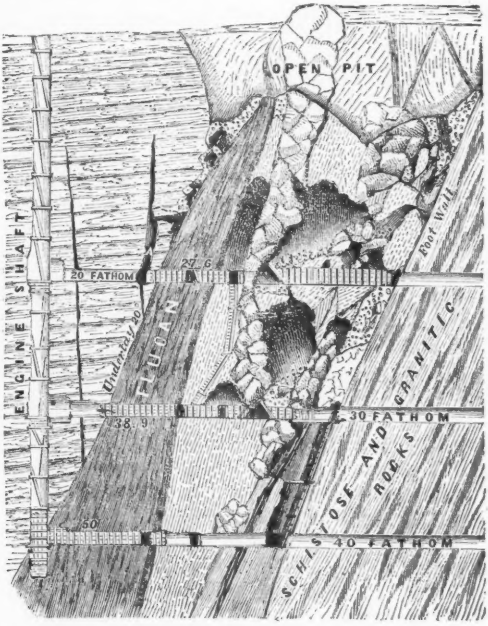

FIG. 25. Diagrammatic section of Bristol Mine, looking southeast, by Silliman and Whitney in 1855, showing ore zone, workings, and sandstone-schist contact.

the illustration. None of the workings are accessible at the present time. Another shaft, said to be 100 feet deep, lies some 500 feet to the south. In addition to the main open cut, old prospect holes, shafts, and tunnels may be seen to the northeast, along what is presumably the contact. Everything is now covered with vegetation so that little can be seen.

Adjacent to the mine are large dumps and tailings from which some idea may be obtained as to the character of the ore and the rocks encountered in the underground workings.

THE ROCKS AND THEIR STRUCTURE.

As was mentioned previously, the ore follows the northeasterly-southwesterly contact between crystalline schists and red sandstone.

Schist.—The crystalline schist at this point is a part of the Hartland schist.[6] It is a strongly foliated, silvery white rock consisting largely of small grains of muscovite. Smaller amounts of quartz and garnet are visible to the naked eye. The garnet occurs as large, well-defined crystals, in contrast to the lens-like crushed quartz grains. Both are surrounded by thin, curved plates of muscovite. The foliation planes trend N. 25° E. and dip at 70° to the east. The formation is considered to be of Ordivician or Silurian age.[7].

Under the microscope the rock is seen to be made up largely of quartz with considerable muscovite and appreciable sericite. An occasional grain of plagioclase may be seen in some sections. Garnet, tourmaline, calcite, biotite, rutile, chlorite, staurolite, and cyanite were also observed.

Pegmatites.—Numerous intrusions of pegmatites occur in the Hartland schist in the vicinity of the mine. They differ considerably in texture and composition; fine-grained varieties have as their chief minerals light-colored, striated feldspar, quartz, and muscovite, while coarse-grained types consist almost entirely of large grains of pink orthoclase feldspar with subsidiary quartz and muscovite. The last-mentioned variety shows relatively little crushing or foliation and must be later in age than the main metamorphism which involved the Hartland schist.

Bristol Granite-Gneiss.—Slightly west of the mine, exposures of the Bristol granite-gneiss may be seen. A few prospect pits

[6] Wm. N. Rice and H. E. Gregory, Manual of Geology of Conn., State Geol. and Nat. Hist. Surv. Bull. 6, 1906, p. 96.

[7] *Idem*, p. 98.

have been sunk in it to explore small quartz veinlets containing chalcopyrite, zincblende, and siderite. Small grains of chalcopyrite are scattered through it. The rock is medium-grained, greenish-gray in color, and has a well-developed structure. Its greenish color is due to the presence of chlorite. Other minerals that may be seen in it are quartz, plagioclase, biotite, rutile, muscovite, tourmaline, calcite, and considerable garnet. The latter forms dark red, small, irregular grains which are segregated into bands parallel to the gneissic structure. Some of this rock was observed near the ore deposit interbanded with the mica schist, into which it appears to be intrusive. The granite-gneiss apparently has undergone nearly as much metamorphism as the Hartland schist, and is decidedly more metamorphosed than the orthoclase pegmatite previously mentioned. All of the above rocks lie on the footwall side of the main ore deposit.

The nature of the rocks where the ore actually occurs could not be seen since the workings are inaccessible. Specimens from the dumps, however, indicate the presence of arkose, mica-schist, and pegmatite.

Granite?—All of the older descriptions of the property make mention of granite. Shepard[8] describes "alternations of vertical layers of granite and soft mica slate. The layers of the granite are one to two feet in thickness, while those of the slate are generally much less."

Percival[9] says "The Bristol Mine is chiefly opened in a large vein of coarse reddish sub-talcose granite."

Silliman and Whitney[10] state that "workings were chiefly in a series of micaceous and hornblende slates, sometimes passing into gneiss, and including large irregular 'horses' of granite, which rock appears to have formed segregation masses, lying rudely parallel with the bedding of the schistose rocks." As no specimens of granite can be seen on the dumps or in the vicin-

[8] Shepard, C. U., Report on the Geol. Surv. of Conn., 1837, p. 47.

[9] Percival, J. G., Report on the Geol. of the State of Conn., 1842, p. 77.

[10] Silliman, Benjamin, and J. D. Whitney, *Amer. Jour. Sci.*, vol. 36, 1855, p. 362.

ity, it is probable that the granite mentioned is arkose or pegmatite. Some specimens of the Bristol arkose, labelled as granite, occur in the Yale collections.

Arkose.—On the east side of the contact is the well-known red arkosic-sandstone of Triassic age that occurs throughout the Connecticut Valley and forms a part of the Newark formation. The position of the sandstone suggests that it is a part of the 6,000 feet of coarse arkose that lies below the lower lava flow, but the exact horizon could not be determined. The sandstone here is relatively coarse grained and is made up chiefly of angular fragments of quartz, fresh orthoclase and plagioclase feldspar, and particles of mica, chlorite, and mica-schist. Alternating with the beds of red sandstone are bands of so-called gray sandstone. These occur only near the contact in the underground workings and are the containers of the sandstone ore. The beds have a northeasterly strike, parallel with the foliation lines of the schists.

Bristol Fault.—The schist and sandstone are separated by a fault and it is along this fault that the main ore body occurs. However, few traces of the actual fault are now visible on the surface. No mention of a fault contact is made by Shepard or Percival, but Silliman and Whitney state that there is "evidence in the confused character of the ground, as well as in the slip joints and polished surfaces of the rocks, that motion of the various beds upon one another has taken place along lines of upheaval of limited extent and varying direction."[11]

The same authors also describe a great mass of "flucan" (see Fig. 22)—an old Cornish term for gouge. This may possibly be fault gouge, though their descriptions do not make this point clear. The "flucan" on the dump is sericitized mica-schist. The dumps, however, display adequate evidence of the existence of faulting, for pieces of slickensided rock and fault gouge are abundant. The latter is mostly a heavy, red, clayey gouge, derived from the red sandstones. Also in an excellent suite of specimens from the Bristol Mine in the Laboratory of Economic

[11] *Idem*, p. 362.

Geology at Yale University, there are several pieces which show slickensides. Copper sulphides have been deposited on these slickensided surfaces, indicating that some faulting took place prior to the metallization. Furthermore, the copper minerals themselves have been slickensided, indicating a recurrence of faulting after the period of metallization. The broken character of the fault zone and its dip may be seen in Fig. 25 by Silliman and Whitney.

Further evidence of the fault is to be seen in a vertical cross-section of the mine (see Fig. 26) made by Messrs. Ricketts and Banks in 1895.[12] This shows that the fault dips eastward at

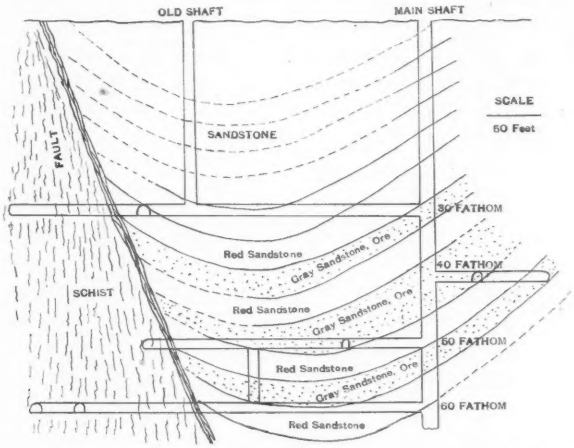

FIG. 26. Cross-section of Bristol Mine from Ricketts and Banks in 1895, showing the Bristol fault and deformed sandstone beds adjacent to it.

an angle of 70° and in this respect it differs from the prevailing westward dips of the many faults that have dislocated the red sandstone of the Connecticut Valley.[13] The same cross-section

[12] Records of the mine in possession of Mr. Wm. Lugg.

[13] Davis, W. M., U. S. Geol. Surv. Eighteenth Ann. Rep., 1898, Part II., pp. 84–137.

shows that the sandstone beds, where cut in the main shaft at the four lower levels, dip westward at an angle of 35°, and then bend upward against the fault so as to have a reverse easterly dip. This dragging upward of the beds against the fault indicates that the eastern, or sandstone, side has been dropped downward and that the fault is a normal one. The westward dip of the sandstone is surprising, in view of the prevailing easterly dip of the Triassic sandstone in Connecticut.[14]

It is believed that the faulting took place during the period of Triassic sedimentation. The reasons for this conclusion are as follows: The fault is obviously later than the sandstones of this locality, and it preceded the ore deposition since ore occurs in the broken fault material and on slickensided sandstone. The ore deposition accompanied the igneous activity (see p. 136) and the igneous activity ceased long before the completion of the Triassic sedimentation; at least 3,500 feet of sandstones were deposited on top of the upper trap floor,[15] and all of the trap intrusives are found only in the sandstones underlying the upper trap flow.

It seems most probable that the ore deposition also ceased not long after the termination of the igneous activity, and certainly before the deposition of 3,500 feet of sediments. Therefore, the Bristol fault was formed after the lower sandstone deposition and before the completion of the upper sandstone deposition. If this reasoning is correct, it follows that the Bristol fault was formed during the time of Triassic sedimentation and preceded the faulting that blocked out the present structure of the Connecticut Newark formation.

THE ORE DEPOSIT.

Nature of the Deposit.—The nature of the ore deposit has to be inferred from the meagre descriptions of it[16] and from a study

[14] *Idem.*

[15] Davis, W. M., "The Triassic Formation of Connecticut," U. S. G. S. Ann. Rept., Part II., 1898, p. 29.

[16] (*a*) Silliman and Whitney, *Amer. Jour. Sci.*, vol. 36, 1855, p. 362. (*b*) Cross-section by Ricketts and Banks, 1885. (*c*) Verbal descriptions and sketches by Mr. Wm. Lugg, former superintendent.

of the ore and rock specimens. It would appear that two classes of ore bodies make up the deposit, namely, (*a*) small irregular veins in the broken material of the fault and in the crystalline schists, and (*b*) disseminated ore in certain gray sandstone beds adjacent to the fault, and to a lesser extent in the schists.

The veins now removed were discontinuous in length and depth and varied in width from six inches to three feet. They wound irregularly through the broken material of the fault zone and followed fractures parallel to the foliation of the schists. In places they were joined by connecting spurs and branches. One vein which varied in width from one to two feet extended into the sandstone. Parts of the veins were occupied by bands of solid copper sulphide up to eight inches thick that yielded sorted ore containing over 50 per cent. copper. A more persistent quartz vein was encountered above the 40-fathom level in the footwall schist about 150 feet from the contact, and was called the Footwall Vein. This vein apparently supplied most of the massive copper mined around 1855. As far as can be ascertained, the vein followed a fault, parallel to the main fault, and probably sympathetic with it. This vein gives way on the 60-fathom level to two smaller and relatively unimportant veins. In places the schist and broken fault material were observed to be impregnated with grains and minute veinlets of sulphides so that the whole formed low-grade ore averaging less than 1 per cent. copper. All of these richer veins above the 40-fathom level were mined in the earlier period of activity. The discontinuous winding nature of the small veins, however, entailed just as irregular workings, consequently the earlier mining resulted in greater expense than profit.

The disseminated ore is largely in the sandstone. The copper sulphides occur in veinlets, scattered grains, and small bunches and pockets. Usually where the sulphides are in seams they are accompanied by quartz, but this is not true of the scattered grains. The veinlets appear to have followed small cracks and fractures. In many respects the sandstone ore resembles the disseminated ore of the modern "porphyry" copper mines.

Most of the sandstone immediately adjacent to the fault appears to have been mineralized with veinlets and, to a lesser extent, with disseminated sulphides. Similar metallization follows at least three gray sandstone beds (see Fig. 26), each separated by a barren red sandstone bed, eastward to the main shaft—a distance, on the 60-fathom level, of 200 feet. These beds curve in a gentle syncline from the contact to the shaft, due to their being dragged up, with a reverse dip, against the fault. They have been developed on the 40-, 50- and 60-fathom levels. The descriptions indicate that the metallization of the gray beds is somewhat spotty.

Character and Grade of Ore.[17]—The mine was worked for copper, but silver added somewhat to the value of the ore. No gold is present. The ore is made up chiefly of a gangue of country rock and vein quartz containing sulphides of copper. The latter, described under the heading of "Mineralogy," consist chiefly of chalcocite and bornite.

The ore first worked consisted of the richer veinlets of chalcocite and bornite, from which the waste material was carefully sorted. There is no record of the grade of ore as mined, nor of the copper content of that which was shipped, but it must have ranged from 40 to 50 per cent. of copper.

In the period from 1847 to 1855 there was sold 2,220 tons of ore of an average grade of 33.2 per cent. copper. The highest grade of the ore was 50.75 per cent. copper and the lowest grade 14.78 per cent. The average copper content of the ore sold in 1849 was 44.67 per cent., while that sold in 1855 was 27 per cent. All of this ore was "dressed" and there is no record of the amount of ore extracted from which the above quantity was obtained, consequently the grade of the ore as broken is not available. Old mine records indicate that during the latter part of this period the low-grade disseminated ore in schist was mined and all of it was concentrated.

In 1885, the disseminated schist ore as mined yielded 0.8 per

[17] The data here given regarding the grade of the ore were worked out from figures supplied by Mr. Lugg, former superintendent of the property.

cent. of copper, and from each 100 tons of it there was obtained 2.68 tons of concentrates containing 30 per cent. copper. Sampling of the disseminated schist ore by Mr. Stadtmuller in 1853 showed it to contain 1.103 per cent. copper, and by Silliman and Whitney in 1855,[18] 0.93 per cent. copper.

The disseminated ore in sandstone was developed during the last period of activity. An average of a number of samples taken in April, 1890, showed this ore to contain 2.89 per cent. copper. In 1895 the sandstone ore was carefully sampled by Ricketts and Banks. The average copper content of all their samples, weighted for the widths of the samples, was 1.54 per cent. A 750-pound sample taken by them for a mill test gave copper—1.12 per cent., gold—trace, and silver—0.30 oz. per ton.

The test showed that the ore could be concentrated readily, yielding 2.52 tons of concentrates for each 100 tons of ore. The concentrates obtained from this test contained copper—30.78 per cent., gold—0.20 oz., silver—25.8 oz.

The data cited above give little information as to the copper content of the ore contained in the veins, but does show that the disseminated ore is low-grade material, even lower grade than much of the ore contained in the disseminated porphyry copper mines of today. The tonnage of disseminated ore now in the mine is unknown.

Wall Rock Alteration.—The schists immediately adjacent to the ore deposit are predominantly light colored. Their composition is about the same as the descriptions previously given for the Hartland schist, though possibly they contain somewhat more sericite; also the tourmaline content is notable. A few feet away from the ore deposit the schists are much darker in color. The obvious conclusion would be that the lighter color and the change in composition of the schist nearest the deposit was due to bleaching and alteration by the metallizing solutions. But this may not necessarily be true because the schist series to start with was characterized by changeable composition from place to place

[18] The cost of mining and dressing the ore at this period is said to have been $1.80 per ton of ore.

and the later pre-ore metamorphism was equally irregular. In places remote from the ore deposit identical composition changes have been observed to take place within a few feet. Also, the character of the alterations has little resemblance to that which usually takes place in the wall rocks of ore deposits formed by means of hydrothermal solutions, but is more typical of changes produced by regional and contact metamorphism.

The large amount of tourmaline in the schist adjacent to the ore deposit needs explanation. It might be inferred that the tourmaline was formed by the same agencies that produced the ore. However, I think that this is not the case. It will be recalled that the locality of the ore is also the site of pegmatitic intrusions. Elsewhere, similar pegmatitic intrusions are accompanied by pronounced metamorphism of the schist and a development of tourmaline; toumaline-bearing pegmatites also occur, and tourmaline occurs as a result of the metamorphism of the Bristol granite-gneiss on the schist.[19] The schist so formed is identical with that which contains the Bristol ore. It is a reasonable assumption, therefore, that the tourmaline in the schist adjacent to the ore was also formed as a result of the intrusions. This conclusion is strengthened by the observation that many of the tourmaline prisms are fractured and crossed by minute quartz veinlets that accompanied the metallization; also a small fragment of tourmaline was observed in the arkose in relations that show it to have been detrital. Therefore it seems more probable that the composition and light color of the schist was caused by pre-ore metamorphism and was not a result of the metallizing solutions. The latter seem to have been such that they were unable to affect the schist appreciably.

The effect of the metallizing solutions on the sandstone adjacent to the fault could not be seen on the surface because of the lack of sandstone exposures. The mine dumps, however, contain both red and gray sandstone. The red sandstone has not been metallized, but the gray sandstone has been impregnated

[19] W. N. Rice and H. E. Gregory, Manual of Geol. of Conn., State Geol. and Nat. Hist. Surv. Bull. 6, 1906, p. 105.

with sulphides. Furthermore, a detailed examination of the mine dumps disclosed the fact that every piece of ore-bearing sandstone is invariably gray in color, and that no gray sandstone free from copper minerals can be found. An intimate association between gray sandstone and ore minerals is thus established. This conclusion corroborates the information contained on the Ricketts and Banks cross-section shown in Fig. 26, that the gray sandstone layers, but not the red ones, are the containers of the ore.

Farther to the east of the ore deposit all of the sandstone beds that can be seen are red in color, and throughout the Triassic sandstone area in general the color of the rock is prevailingly red. The gray sandstone, then, is a local feature and is confined to the immediate vicinity of the ore. This indicates that the gray color of the sandstone and the formation of the ore are due to one and the same cause—the metallizing solutions.

The red color of the normal Triassic sandstone is due, not to the constituent grains that make up the rock, but to the cementing material which contains an appreciable amount of ferric oxide.[20] The gray sandstone is simply the red sandstone from which the ferric oxide cementing material has been removed. The metallizing solutions, then, were able to, and did, remove the ferric oxide from the sandstone.

A surprising feature of the alteration of the sandstone is that the altering solutions apparently produced no other effect upon the rock than the removal of the ferric oxide. The normal red sandstone is arkosic and contains numerous angular shiny fragments of orthoclase and plagioclase. The feldspar fragments are just as shiny and fresh in the well-metallized gray sandstone as in the normal red rock. The metallizing solutions that were able to deposit quartz and sulphides and remove ferric oxide, and yet not affect the feldspar, must indeed have been unusual.

Age of Deposits.—From the descriptions given above, it is obvious that the ore deposit is later in age than the enclosing Triassic sandstone. It is also later in age than the fault that

[20] Russell, I. C., U. S. Geol. Surv. Bull. 52, 1889, p. 44.

dislocated the sandstone. Further than this there is no conclusive evidence.

It is strongly suggestive, however, that the formation of the ore took place before the conclusion of the Triassic sedimentation. The ore deposition is believed to have been a phase of the igneous activity that gave rise to the intrusive and extrusive traps and, as shown on page 130, the igneous activity ceased long before the end of Triassic sedimentation. The ore deposition in all probability likewise ceased before the end of the laying down of the Newark sandstones.

The connection between the ores and the volcanic activity can not be conclusively established, but certain features strongly suggest such an association. For example, deposits which contain ore similar to that at Bristol are widely scattered in Connecticut, yet nowhere are they found outside of the area occupied by the Newark sandstone and its associated trap rocks. The traps themselves are also known to contain copper. Further, in New Jersey[21] and Pennsylvania[22] the Newark series consists of red arkosic sandstones and associated trap rocks that are identical in character and age with the Connecticut and Massachusetts occurrences. Throughout the Triassic area of these states are numerous deposits of copper that occur in the traps themselves, in the sandstone adjacent to the trap, and in sandstone remote from trap. Also at Cornwall, Pennsylvania, contact metamorphism by Triassic diabase produced cupriferous magnetite deposits,[23] thereby proving that the trap magmas gave off copper. Lewis[24] concludes that the copper of the New Jersey deposits was derived from the trap rocks during the time of their cooling, and Wherry[25] holds the same opinion for the Pennsylvania Newark copper de-

[21] J. Volney Lewis, "Copper Deposits in the New Jersey Triassic," Econ. Geol., vol. 2, 1907, pp. 242–257.

[22] E. T. Wherry, "Newark Copper Deposits," Econ. Geol., vol. 3, 1908, pp. 726–738.

[23] A. C. Spencer, "Magnetite Deposits of Cornwall, Pa.," U. S. G. S. Bull. 359, 1908, p. 15.

[24] *Loc. cit.*, p. 257.

[25] *Loc. cit.*, p. 731.

posits. This intimate association between similar copper deposits and the trap rocks in so many widely separated localities of the Triassic area can hardly be a coincidence. It is a justifiable inference, therefore, that the copper deposits, including the Bristol deposit, were connected genetically with the igneous activity and, consequently, are of Triassic age.

MINERALOGY OF DEPOSITS.

Gangue Minerals.

Quartz and calcite are the most abundant of the gangue minerals that were introduced at the time of metallization, and of these quartz is by far the more important. Lesser amounts of barite and siderite also accompanied the ore minerals. A part of the ore minerals found a resting place in the sandstone and schist without any accompanying gangue substance. As mentioned previously, it is believed that the tourmaline that occurs so abundantly in the mica schist was not an accompanier of the metals, but was formed during a period or periods of metamorphism that preceded the metallization.

Quartz.—While the total amount of vein quartz is not great, it is conspicuous by its pronounced tendency to occur in well-formed crystals. These are to be seen as linings of the walls of small veinlets and larger fractures, as radiating coatings around fragments of rock, and as the fillings of small cavities. The individual crystals are pronouncedly prismatic, and the free end of each prism is terminated by the rhombohedral faces, giving rise, in most cases, to perfect hexagonal pyramids. Occasionally the rhombohedral faces are irregularly developed. While there is an absence of trigonal trapezohedrons or intergrowths of the right- and left-handed quartzes, such as are considered by Wright and Larsen[26] to indicate the low-temperature form of quartz, there is also an absence of the hemihedral forms of the higher temperature variety; the prismatic habit, and the irregular development of the rhombohedrons, however, suggest the low-tem-

[26] Wright, E., and E. S. Larsen, *Am. Jour. Sci.*, vol. 27, 1909, p. 438.

perature form. The individual prisms are never doubly terminated, but extend outward from a base of small interlocking quartz grains devoid of crystal faces, and present an arrangement commonly referred to as comb structure. Some of the quartz also resembles the "cockade" and "drusy" quartz of Adams.[27] Such crystals of quartz which occur throughout the ore in the manner described above are usually considered to indicate their formation in free spaces and at shallow depths.

Veinlets of massive quartz which range from a fraction of an inch to a foot or more in width are also to be observed. Under the microscope they are seen to be composed of small interlocking grains without crystal faces, and are almost invariably accompanied by copper minerals. Such veinlets of microscopic size cut across large quartz crystals which exhibit shadowy extinction, thereby indicating an age difference between the quartz which accompanied the metallization and the older quartz of the pegmatites. This age distinction is of interest, inasmuch as large hand specimens may be obtained which show copper minerals scattered through pegmatitic quartz and thereby open the possibility that the copper was an accompanier of the pegmatite. But the microscope invariably shows that the sulphides accompany later quartz veinlets which traverse the older strained quartz, and this pegmatitic quartz is simply by accident a resting place for the copper mineralization of no greater importance than the schist or sandstone.

The quartz preceded, accompanied, and followed the copper sulphides, since quartz and chalcocite are intergrown, and chalcocite crystals are developed on top of drusy quartz crystals and vice versa. However, most of the crustified quartz was formed earlier than the copper sulphides because the latter usually occupies the centers of the veinlets, and chalcocite crystals on top of quartz crystals are far more frequent than the reverse order.

Calcite.—Of the gangue minerals introduced during the period of copper mineralization, calcite is next in importance to quartz, although it is much less abundant than the latter. Its most com-

[27] Adams, S. F., Econ. Geol., vol. 15, 1920, pp. 636 and 638.

mon occurrence is in the massive form, although drusy spaces lined with dog-tooth crystals are not rare.

The massive calcite is in the form of small veinlets and since it is usually separated from the wall rocks by an intervening lining of quartz, it must have been formed later in the period of mineralization than the massive quartz. The massive calcite seems always to have been accompanied by bornite, and the petrographic microscope shows that the two were formed simultaneously.

The crystallized calcite is to be observed more frequently than the massive variety, and in this form it occurs intimately intergrown with chalcocite crystals. In some cases small calcite and chalcocite crystals form porous friable masses of irregular shape; if the calcite is dissolved out by acid, the chalcocite crystals fall apart—the two must have been deposited simultaneously.

More commonly, however, the calcite occurs, along with remarkable crystals of chalcocite, as acute scalenohedrons on the walls of open fractures and in druses. Their intimate relationship renders the conclusion inescapable that they were formed at the same time. The dog-tooth calcite crystals and the chalcocite crystals were the last minerals to be formed in the deposit.

Barite.—Barite was noted in one large hand specimen only and was not actually observed in place. The specimen, about ten inches long, is reported to have come from the southwest corner of the main ore body and consists of quartz, chalcopyrite, pyrite, and much barite. The latter occurs chiefly as thin plates up to a square inch in area. It is intimately intergrown with chalcopyrite and the two apparently have been formed at the same time. The massive chalcopyrite and the pyrite which are associated with the barite are just as rare as the barite. Barite also occurs with chalcocite and malachite in a vein which traverses the red Triassic sandstone at Cheshire, Conn.

Siderite.—A small amount of siderite was seen in ore from the dump at the South Shaft. It is associated with chalcopyrite, pyrite, and zincblende. It was also observed in stringers about one quarter inch wide cutting the Bristol gneiss at a point about 200 feet west of the main ore body. Small specks of chalcopyrite may be observed in the siderite.

Ore Minerals.

The Bristol deposit does not include a great variety of ore minerals. Only three, chalcocite, bornite, and chalcopyrite, are present in appreciable amounts; and of these, chalcopyrite is relatively subordinate. Other minerals that were noted, either in the hand specimen or by aid of the microscope, are covellite, pyrite, sphalerite, and galena, and all of them are rarities. A few tiny specks of an unidentified creamy white mineral were observed in bornite by means of the high power of a reflecting microscope. Native copper is entirely absent from the deposit, but a trace of cuprite was seen.

Chalcocite, Bornite.—The Bristol chalcocite is widely known in museums and research laboratories of the world for its remarkable crystal development—a consideration that has made the deposit more famous than its commercial development would justify. But the crystals, although beautiful and interesting, are only a spectacular feature of the deposit and the greater part of the chalcocite occurs in massive form. It is the chief mineral of the disseminated ore and constitutes around fifty per cent. of the copper sulphides. The bornite is slightly less in amount.

In hand specimens the chalcocite appears as small blebs and veinlets in the disseminated ore, and usually as an intimate mixture with bornite, in the veins. However, veinlets of either relatively pure chalcocite or pure bornite also occur. The bornite appears to be in much greater proportion where the ore occurs in schist than where it is enclosed in sandstone.

The hand specimens also show that the sulphides and quartz were formed simultaneously and also alternated in their deposition; layers of quartz lined the walls, then, in places, massive copper sulphides. Comb quartz was deposited on the massive sulphides and delicate orthorhombic chalcocite crystals nestle on top of the quartz pyramids. In places, slender dog-tooth crystals of calcite were deposited simultaneously with the chalcocite crystals. The crystals of these two minerals were the last products to form. The contemporaneity of the calcite and chalcocite seems

convincing. Rare crystals of bornite are also to be seen as linings of drusy cavities. The structure of the ore and the arrangement and location of the numerous crystals all testify to ore deposition in free spaces.

The reflecting microscope shows that most of the disseminated chalcocite in the bleached arkose is a pure white chalcocite with only occasional blebs of bornite. In the disseminated ore in schist, however, more bornite is present. The massive vein sulphide, on the other hand, is seen to be an intimate mixture of bornite, chalcocite, and occasionally chalcopyrite, but there may be also pure chalcocite, pure bornite, or pure chalcopyrite. Generally chalcopyrite and chalcocite do not occur in the same specimen in appreciable amounts, but the common association is bornite-chalcopyrite and bornite-chalcocite.

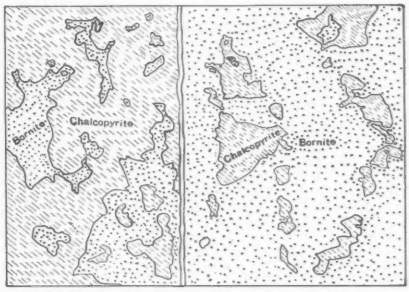

FIG. 27. Camera lucida drawing of polished specimen of Bristol ore (× 60), showing one type of relations between bornite and chalcopyrite. Left, bornite in chalcopyrite; right, chalcopyrite in bornite. Note similarity to chalcocite-bornite mixture in Fig. 28. Each side represents half-fields in different parts of same specimen. (Difference in size of half-fields due to distortion by camera lucida.)

In the bornite-chalcopyrite mixtures the two minerals under the microscope exhibit sharp, smooth boundaries toward each other, and areas of bornite are included in chalcopyrite, and vice versa. These relations may be seen in part in Fig. 27. The individual mineral areas have both rounded and angular outlines.

If the colors were absent one could not, from the structure alone, distinguish the two minerals. The structure is identical with that commonly found between bornite and chalcopyrite in copper deposits of unquestioned hypogene origin. In the Bristol ore the relations of these two minerals toward each other are such as to suggest that both are hypogene minerals and were deposited essentially at the same time, though with a tendency for much of the chalcopyrite to be slightly later in age than the bornite. Chalcopyrite also occurs in other structures, to be mentioned later.

In most of the bornite-chalcocite mixtures the same textural relations hold. The two minerals are generally mutually enclosed in each other and, as may be seen in Figure 28, the

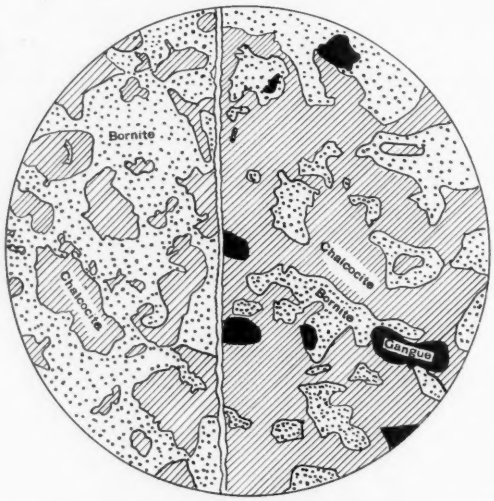

FIG. 28. Camera lucida drawing of polished specimen of Bristol ore (× 60), showing relations between chalcocite (shaded) and bornite (stippled). Left side represents one half of a field showing chalcocite included in bornite; right, another half-field of same specimen showing bornite included in chalcocite. Compare shapes of inclusions with those contained in chalcocite crystal, Fig. 29. (Difference in size of half-fields due to distortion by camera lucida.)

boundaries between them are sharp and smooth. If it were not for the color differences, one could hardly distinguish the greater part of the bornite-chalcocite mixtures from the chalcopyrite-bornite mixtures; the structures are those to be found generally with hypogene minerals. The two minerals were in large part formed simultaneously, and if the bornite is a primary mineral much of the chalcocite should also be so considered.

While the relations just described exist for most of the bornite-chalcocite mixtures, some of them exhibit different structures. For example, the well-known graphic intergrowths between bornite and chalcocite, such as have been pictured and described by several investigators,[28] are frequently to be seen. As such intergrowths in the Bristol ore have already been discussed by Whitehead [29] and Rogers,[30] no further description of them is necessary. Again, occasional veinlets of chalcocite cut across areas of bornite. Such veinlets, however, usually do not hold the relations to bornite such as are seen with clearly defined supergene chalcocite enrichment; there is an entire absence of chalcocite with the structures so well known in copper deposits that have undergone chalcocite enrichment by supergene processes. A few specimens also show embayment of bornite by chalcocite and some of the chalcocite replaces bornite. These features, however, I regard as due to an overlapping of hypogene mineralization between chalcocite and bornite, in which much of the chalcocite and bornite were formed simultaneously, but the chalcocite continued to grow after most of the bornite had been deposited, and in a few places corroded and replaced the previously formed and temporarily unstable bornite.

The crystals of chalcocite occur as individuals or clusters and are to be found wherever open spaces exist. They have reared themselves on massive sulphides, on massive quartz or calcite, on

[28] Graton, L. C., and Murdoch, J., Amer. Inst. Min. Eng. Bull. 77, pp. 741–811, 1913. Laney, F. B., Va. Geol. Surv. Bull. 14, 1917, pp. 82–89. Whitehead, W. L., Econ. Geol., vol. 11, 1916, pp. 1–13. Rogers, A. F., Econ. Geol., vol. 11, 1916, pp. 582–593. And others.

[29] *Loc. cit.*

[30] *Loc. cit.*

comb-quartz crystals, and on schist. Some of them were deposited simultaneously with quartz or calcite crystals, and usually the chalcocite and calcite crystals were the last minerals to be formed. The Bristol Mine has supplied some of the world's best crystals of chalcocite, consequently descriptions and drawings of them are to be found in most text books of mineralogy. They are tabular in form, parallel to the base and are pseudo-hexagonal in symmetry. They are almost invariably twinned and striations on the base are pronounced.

Many of the chalcocite crystals were oriented, polished, and examined under the reflecting microscope. For the most part they consist of pure white chalcocite, but a number of them contain specks of bornite with the same smooth sharp boundaries and with rounded or angular outlines (Fig. 29). The bornite is

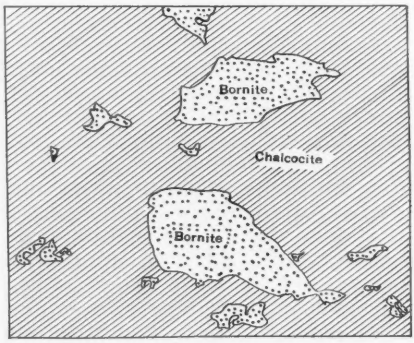

FIG. 29. Camera lucida drawing of polished chalcocite crystal, Bristol ($\times$ 70), showing inclusions of bornite. Note similarity of shapes of bornite inclusions with Fig. 28.

most common nearest the points of attachment, but was also observed within the centers of the crystals in different positions. The relations of the chalcocite and bornite are identical with that already described and there is no hint of replacement of one by the other. As the crystal habit is typical of that for chalcocite—

in fact the type examples—it is clear that their form can hardly be pseudomorphic after any other mineral and that this chalcocite is the result of direct deposition from solutions and not of replacement.

The crystals, as well as all of the other chalcocite, when etched by different reagents, reveal typical orthorhombic etch lines. There is no suggestion of any isometric etch lines, nor are any cleavages or partings ever found to extend from chalcocite into bornite. Inclusions of chalcocite in bornite, or of bornite in chalcocite, when etched, show by the directions of the cleavage lines that the individual areas of chalcocite are variously oriented, suggesting that each chalcocite individual had its independent growth.

Chalcopyrite.—Chalcopyrite is a prominent constituent of the Bristol ore though subordinate in amount to the chalcocite and bornite. Usually it is intimately associated with bornite, though a few specimens are on hand of massive pure chalcopyrite with quartz and barite, all three minerals having been formed approximately at the same time. Rare crystals of chalcopyrite are also to be observed in drusy openings. Practically all of the chalcopyrite occurs in the veins; none was noted with the disseminated chalcocite in sandstone and only a few specks were found with disseminated bornite in schist. At some distance from the ore deposit, however, occasional specks of chalcopyrite are scattered throughout the Hartland schist and Bristol gneiss.

With the reflecting microscope three modes of occurrence of chalcopyrite are to be seen—namely, essentially contemporaneous intergrowths with bornite, such as have already been described (see Figure 27), later replacements of bornite, and along cracks in bornite in association with covellite.

In the second mode of occurrence, chalcopyrite embays and cuts across bornite. Frequently it is to be seen as parallel sharp gashes along cleavage lines of bornite, or as rims surrounding individual grains. In one instance, chalcopyrite appears to shoot all through a bornite area in a form resembling the aurora borealis; faded bornite residuals are scattered throughout the in-

vading chalcopyrite. These occurrences are in relations that offer no other interpretation than that of replacement of bornite by chalcopyrite.

In the third mode of occurrence, the chalcopyrite occurs along little cracks that traverse bornite and chalcocite, but is confined entirely to the bornite areas (see Figure 30). In such positions

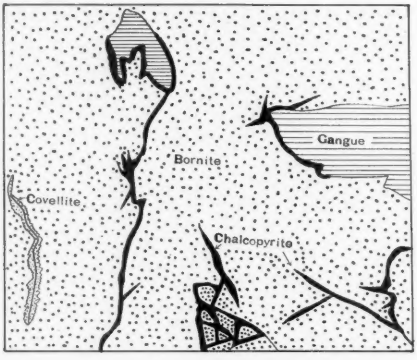

FIG. 30. Camera lucida drawing of polished Bristol ore (× 60), showing veinlets and gashes of chalcopyrite and covellite in bornite. Veinlets of both minerals follow small fractures, but chalcopyrite gashes do not. Note rimming of gangue inclusions by chalcopyrite. Example of secondary structure (probably supergene). Compare with Figs. 27, 28, 29.

it is associated with covellite that also follows the cracks. The two minerals appear to have formed at about the same time and are later in age than the chalcocite and bornite. This occurrence will be referred to further under the discussion of covellite.

Covellite.—Traces of covellite are occasionally to be seen under the microscope. Almost invariably it follows cracks and occurs in bornite or chalcopyrite areas, but never in chalcocite (see Figure 30). Occasionally it forms a disconnected rim around bornite or chalcopyrite where these sulphides are in contact with gangue minerals. The amount of such covellite is so small as to

be almost negligible. Its position with respect to the other sulphides is similar to that usually found in supergene enrichment, and I interpret it as evidence of a trace of supergene enrichment in the Bristol ore. Its behavior to the other copper minerals is in such striking contrast to the relations already described for chalcocite and bornite that each occurrence illuminates the other by light of contrast.

Pyrite.—This mineral is of such rare occurrence that it was observed in only one hand specimen—a large specimen of chalcopyrite and barite that is supposed to have come from the margin of the deposit near the surface. The pyrite is scattered in distorted cubes and pyritohedrons on the walls of drusy openings; some of it is massive. One area only was seen under the microscope. A few grains of pyrite—presumably once part of a single grain—are traversed by chalcopyrite in relations that indicate replacement of pyrite by chalcopyrite.

Sphalerite and Galena.—The 100-foot shaft south of the main ore body penetrated ore containing considerable sphalerite and a little galena. Both sulphides are enclosed in quartz veinlets which cut schist and pegmatite. The relation of these sulphides to the bornite and chalcocite could not be determined. The sphalerite contains minute inclusions of chalcopyrite and considerable gangue. Both sphalerite and galena were deposited before all of the quartz had been formed and the sphalerite is moulded against the cubes of galena.

THEORETICAL CONSIDERATIONS.

Origin of Chalcocite.

The origin of the Bristol chalcocite is of interest because of the light it may throw on the origin of chalcocite in general—for the link it may form in the growing chain of evidence that serves to distinguish supergene and hypogene chalcocite. Whether the chalcocite of any copper deposit is of hypogene or supergene origin is, of course, of great economic importance in the proper understanding and development of an ore deposit.

although this consideration does not enter in with respect to the Bristol deposit. A supergene origin has already been advocated for the Bristol chalcocite by Whitehead,[31] though with no supporting evidence, and the thesis of the present writer is for a hypogene origin, the evidence for which may be considered under several sub-headings.

Mineral Distribution Evidence.—The Bristol deposit has no zonal arrangement of oxidized material, sulphide-enriched ore, and primary mineral matter, such as usually occurs in deposits that have undergone superficial alteration. Surface oxidation is almost entirely absent, and no change in character or mineral content of ore with depth has ever been noted. There is simply the one zone—the mineral deposit. Had supergene enrichment taken place, it is true, of course, that the oxidized zone probably would have been removed by glaciation and that the workings may not have extended deep enough (378 feet) to penetrate the primary material beneath. While this is a possible consideration, there is, however, no evidence in support of it. The only locality where pyrite has ever been observed was near the surface, likewise the most abundant chalcopyrite occurred near the surface, and this chalcopyrite is the freshest of the minerals that have been examined. There is no trace on it of sooty chalcocite or covellite such as would be expected if the chalcocite below it had been formed by descending enriching solutions. Similarly, the bornite near the surface is free from coatings of covellite or sooty chalcocite. The sphalerite and galena at the surface are also fresh, and the latter is a mineral which usually alters in part to covellite in the presence of downward enriching solutions. No change in the proportions between chalcocite and the other copper sulphides with increase of depth has been noted.

It is thus evident that the distribution of minerals does not indicate any zonal arrangement. On the contrary, the features mentioned above suggest the absence of any superficial alteration and enrichment. Had appreciable secondary enrichment taken

[31] Whitehead, Econ. Geol., vol. 11, 1916, pp. 1–13.

place one should expect at least some evidence of coatings of secondary sulphides upon the other minerals.

The occurrence of calcite as a gangue mineral throughout the ore deposit is difficult to reconcile with descending sulphate, and probably acid, solutions, such as would have trickled through the deposit if the chalcocite were to be ascribed to supergene processes. Furthermore, the chalcocite crystals held together by calcite, described on page 139, show that the two were deposited simultaneously, and if the chalcocite be considered to have been formed by descending sulphate waters, then so must the calcite. Such a consideration is out of keeping with supergene enrichment, but is commonplace with hypogene metallization.

Crystals as Evidence.—The argument just mentioned applies with equal force to the intergrown crystals of chalcocite and calcite which were the last minerals to grow upon the walls of many of the drusy openings.

The presence of large, well-formed chalcocite crystals in drusy openings, indicating, as they do, growth in free spaces and without replacing other sulphides, are features of hypogene rather than supergene mineralization. Also the contemporaneous growth of interlocking quartz crystals and chalcocite crystals, each with their own crystal outlines, proves that the solutions which deposited chalcocite also deposited quartz. To consider that the quartz crystals could have been deposited from cold sulphate waters violates our conceptions of supergene processes, but their formation by means of hypogene solutions is a fundamental of ore deposits.

Microscopic Evidence.—It has been mentioned already that investigation of polished specimens shows that most of the chalcocite is in such relations to bornite as to indicate that the two were formed simultaneously. Identical relations exist between the bornite and the chalcocite in the chalcocite crystals, and reasons have been advanced for concluding that the crystals were formed from hypogene solutions. If this reasoning is correct, it follows that the massive chalcocite also was formed from hypogene solutions.

The part of the chalcocite which corroded and replaced bornite (see page 143) certainly was formed later than the bornite, and its presence may be ascribed to either hypogene or supergene solutions. Microscopic examination alone offers no conclusive evidence on this point. However, the character of the replacement is that commonly found between hypogene minerals of slightly different age, and bears no resemblance to the structures so well known by geologists to characterize supergene enrichment chalcocite. As previously mentioned, the writer believes this type of replacement of bornite by chalcocite to be due to a slight overlapping of deposition of chalcocite on bornite during the original metallization, in which chalcocite continued to grow later than the bornite, and, due to a change in the concentrations of ions, the solutions, at the same time they deposited chalcocite, attacked the temporarily unstable bornite. This feature has an analogy in the corrosion and embayment of quartz in igneous rocks by other minerals.

Another line of microscopic evidence lies in the lack of mottled chalcocite, blue chalcocite, or chalcocite with "lattice" structure, such as is usually to be found in chalcocite that has formed from replacement of bornite or other minerals, whether by supergene or hypogene solutions. All of the Bristol chalcocite grains are clear white by reflected light and remarkably pure. One accustomed to the study under the microscope of polished specimens from secondary enriched copper deposits is struck at once by the contrasts afforded by the Bristol chalcocite. In fact, it was this feature that led the writer into a further investigation of the Bristol ore deposit.

Microscopic examination of the ores with both the reflecting and petrographic microscope discloses numerous small fractures through the sulphides. Along some of them there is a little later chalcopyrite and covellite. But it is notable that the main part of the chalcocite is entirely unrelated to such cracks—a condition which would not be expected if the chalcocite were formed by supergene processes at a later period than the original metallization. The covellite and chalcopyrite veinlets, on the other hand,

may well have been formed by later supergene solutions, and thus represent an incipient supergene enrichment of the deposit.

Etching of the polished surfaces by reagents gives a monotonous repetition of orthorhombic cleavage in the chalcocite. No inherited or other structures were obtained which might suggest that the chalcocite took the place of other minerals.

Rock Alteration Evidence.—Where supergene chalcocite enrichment has taken place it is usual to find that the wall rocks of the deposit have suffered considerable alteration;[32] the development of kaolin is conspicuous. This is true particularly of rocks which contain feldspars. The Bristol wall rocks are remarkably free from such alteration; the schists contain little or no kaolin and the arkosic sandstone has only a trace. The orthoclase and plagioclase feldspars of the latter are remarkably free from kaolinization, and feldspars are usually susceptible to attack by descending enriching solutions. The sericite of the schists—a mineral which readily goes over to kaolin under attack by acid and sulphate waters of enriching copper solutions—shows no evidence of kaolinization. These features strongly suggest that the chalcocite was not formed by downward enriching solutions.

Conclusions.—The various lines of evidence considered alone, while not conclusive, unite in suggesting the improbability of the Bristol chalcocite having been formed by supergene solutions; no less do they indicate the probability of an origin by hypogene solutions. The collective weight of evidence, in my opinion, is preponderantly in favor of the conclusion that the Bristol chalcocite was formed from hypogene solutions and is not the result of secondary enrichment.

Process of Ore Formation.

The vehicle by which the metals and gangue substances were introduced to their present resting place evidently was aqueous solution. The drusy openings lined with crystals, the character

[32] Emmons, W. H., "Secondary Enrichment of Ore Deposits," U. S. G. S. Bull. 625, 1917, p. 479.

of the minerals, and the crustification structure, all point to this conclusion.

Two processes have operated to produce the Bristol ore deposit —cavity filling and replacement—and of these the former was the most important. The crustified appearance of the vein matter, the alternations of quartz, calcite, and sulphides, and the crystals in drusy openings prove deposition in preëxisting cavities. Similar evidence is to be found on a microscope scale where veinlets of quartz or calcite with accompanying sulphides follow and fill small fractures without replacing their walls. Instances were noted in both polished and thin sections where chalcocite had entered along cleavage planes in schist or in mica, and pushed aside or bent the schist foliæ or shreds of mica without replacing them.

Evidences of replacment are also abundant. Replacement of sulphides by sulphides has already been noted and the microscope shows that sulphides in places have replaced massive vein calcite, but never quartz. The muscovite was also resistant to replacement, likewise orthoclase, but plagioclase succumbed in a few instances. The chlorite in the schist and arkose seems to have been the mineral most susceptible to attack. Replacement is most conspicuous in the disseminated ore of the sandstone, the chalcocite blebs having been deposited by this process almost entirely. The cementing material (chiefly calcite), chlorite, and plagioclase are the minerals most affected.

Origin of Ore Deposit.

In a consideration of the origin of the Bristol deposit there are involved questions regarding the source of the material now at rest in the ore body; the character, temperature, and source of the solutions that introduced the ore; the evidence yielded by the nature of the rock alteration and the part played by the ferric oxide of the sandstones, and finally the factors influencing the deposition of the ores and the variety and sequence of the ore minerals.

Character of Metallizing Solutions.—The nature of the solutions that produce ore deposits is usually a matter of conjecture and in this respect the Bristol deposit is no exception. Even if conjecture has to be relied upon, it does not follow, however, that this phase of the problem should be avoided, since any light that may be thrown on it is of value to a proper understanding of ore deposits.

In the case of the Bristol deposit it is definitely known that the solutions were able to transport, and did bring in, silica, calcite, copper, silver, sulphur, traces of other metals, and perhaps some iron and sulphates. It is also definitely known that they were capable of dissolving and removing ferric oxide from the red arkosic sandstone. Further than this, one must rely on deductions or conjecture, and in this connection the nature of the chemical reactions that went on in the original solutions to produce so unusual a hypogene mineral as chalcocite allures one.

The iron contained in the chalcopyrite and bornite may have been an original constituent of the mineralizing solutions or it may have been derived by leaching the ferric oxide from the Newark sandstone. The small amount of iron in the ore is not out of keeping with the latter suggestion. Ferrous ions must have been taken into solution when the ferric oxide was leached and it is quite possible that some of them would combine with sulphur and copper to form chalcopyrite or bornite depending upon the relative concentrations of iron and copper in the solutions. It is now known that chalcopyrite is composed of the cupric and ferrous sulphide molecules.[33] Under such conditions it might be conceived that the solutions to start with were low or lacking in iron and that with the first small amount of leaching of the sandstone, ferrous iron was added to form bornite. Later accessions of ferrous iron obtained by continued leaching of the ferric oxide would give greater concentration of ferrous iron to form chalcopyrite, alternating with bornite in its deposition.

[33] Burdick and Ellis, *Amer. Chem. Soc.*, vol. 39, 1917, p. 2518, give the X-ray structure of chalcopyrite which is interpreted by E. T. Wherry (private communication).

Still more complete leaching of the ferric oxide would yield even greater concentration of ferrous ions producing conditions for the deposition of more of the higher iron mineral, chalcopyrite —the later chalcopyrite which replaces the bornite. While such considerations are speculative, they are, however, interestingly suggestive. If true there would be provided an adequate explanation for the different pulsations of mineral deposition, with intermingling and overlapping between chalcopyrite and bornite, and for the unusual replacement of bornite by chalcopyrite—the reverse of the alteration which usually takes place.

As has been pointed out, the leaching of such an insoluble oxidized compound as ferric oxide from the red sandstone indicates that the ore solutions were reducing in character. When the writer read the interesting paper [34] by Singewald and Berry on the Corocoro deposits of Bolivia, he was struck by certain similarities between those deposits and that of Bristol, and the possible application to the Bristol ore of the idea of Steinmann as used by Singewald and Berry of the part played by ferric oxide in the oxidation of the sulphur of the solutions. It seems probable, as suggested by Steinmann and adopted by Singewald and Berry, that reduction and solution of ferric oxide would provide extra oxygen which would combine with the sulphur of the mineralizing solutions. But it must be remembered that such a reaction has not been actually established. Under such conditions sulphates would probably be formed and herein may lie the explanation for the occurrence of barite in the Bristol deposit. The deposition of barite would be expected because of its insolubility, but if other sulphates, such as calcium or ferrous sulphate, were formed, they would probably be carried away in solution. No evidence of sulphates, other than barite, has been found in the ore. In this connection it is of interest to note that at Cheshire, Conn., there are copper veins in the red sandstone that contain chalcocite, bornite, and native copper in barite. The last

[34] "Geology of the Corocoro Copper District of Bolivia," the Johns Hopkins University Studies in Geology, No. 1, 1922, by J. T. Singewald, Jr., and E. W. Berry.

occurred in such abundance that the veins were formerly worked for the barite itself.[35]

The oxidation by ferric oxide of the sulphur in the ore solutions would diminish the amount of sulphur available for combination with the copper, and deposition of copper minerals low or lacking in sulphur should be expected.

When we scrutinize the Bristol deposit in the light of this working hypothesis we find that chalcocite, the cuprous sulphide, is in abundance; some of it is contemporaneous with bornite and some is later, and the crystals of chalcocite were formed last. Bornite and chalcopyrite—minerals with the cupric molecule—are not later that the cuprous sulphide. The order of deposition is, then, from the cupric to the cuprous sulphides, or in decreasing order of their sulphur content.

The occurrence of ore at Bristol is not incompatible with this hypothesis—in fact the latter would provide an adequate explanation for many of the Bristol phenomena. For example, the overlapping of chalcocite on bornite may have been synchronous with the inflow of solutions in varying states of oxidation, depending on the amount of ferric iron dissolved during their journey through the red sandstone. When, for a time, waters with their sulphur content less oxidized reached the seat of deposition, bornite might be formed; another pulsation of waters with greater oxidation of the sulphur content might produce chalcocite, with perhaps some simultaneous corrosion of the previously formed bornite. If the oxidation of the sulphur in the solutions had gone on still further, native copper might have resulted and perhaps that is the explanation of the native copper at Cheshire and other Connecticut copper occurrences.

Whether chalcocite or native copper be produced would depend upon either the amount of sulphur originally present in the solutions, or the amount of ferric oxide available for oxidation of the sulphur in the solutions. With sulphur in consider-

[35] "Manual of Geology of Conn.," W. N. Rice and H. E. Gregory, State Geol. and Hist. Surv. Bull. 6, 1906, p. 196.

able excess over the amount that could be oxidized by the available ferric oxide, then chalcocite and no native copper would be expected. If the excess of sulphur be small, then some native copper, such as at Cheshire, might be produced along with chalcocite. If the ferric oxide be in excess, or original sulphur lacking, then native copper should be expected. As to which of these is the controlling factor is largely a matter of conjecture, for there is no means of ascertaining the amount of sulphur originally present in the ore solutions, nor the amount of oxidation of sulphur by reduction of ferric oxide at any one time. The amount of ferric oxide removed from the wall rocks would afford little help, for that would indicate simply the total amount of ferric oxide removed during the whole period of mineralization, and vast quantities of solutions may have circulated past a given amount of ferric oxide and taken into solution only a small amount of it at a time. In the Bristol deposit where cuprous sulphide but no native copper occurs, it is clear that if oxidation of sulphur by the ferric oxide of the red sandstone took place, the amount of sulphur in the solutions was in excess of that which could be oxidized by the ferric oxide. In the Cheshire deposit, as advocated by Singewald (based upon Steinmann's suggestion) for the Corocoro deposits of Bolivia, the balance between the total sulphur and the sulphur oxidized by ferric oxide must have been a delicate one, since both chalcocite and native copper were formed.

In the case of the Bristol deposit it is clear that the ferric oxide of the red sandstone was reduced and removed in solution; that there is an abundance of copper sulphide low in sulphur content and that this cuprous sulphide was the last mineral to form; and that a sulphate is present in the ore. It seems probable, therefore, that the reduction of the ferric oxide involved also oxidation of the sulphur of the solutions and accounts for the presence of the abundant hypogene chalcocite in the deposit. It would also account for the succession of earlier formed cupric minerals higher in sulphur. Furthermore, it would provide an adequate explanation for the succession of earlier formed min-

erals higher in iron content, and later minerals with no iron content, because in the earlier stages of deposition where the sulphur of the solutions had not as yet been greatly oxidized, sufficient sulphur was available to combine with some iron after satisfying the copper. In the later stages when reduction of the ferric oxide was more complete and sulphur of the solutions consequently more oxidized, the amount of sulphur was no more than sufficient to satisfy the copper, with the result that only copper sulphide was formed, and that even in a cuprous state.

The realization of the effect of ferric oxide as applied above depends, however, upon the actual chemical establishment that ferric oxide does oxidize the sulphur from such solutions.

In one of the most careful pieces of field and laboratory work in economic geology ever carried on, the Geological Department of the Calumet and Hecla Mining Co., under the leadership of L. C Graton, has been testing out the influence of ferric oxide in the formation of the native copper deposits of the Lake Superior region. In a most noteworthy and stimulating paper (whose publication in full is awaited with interest) presented by the members of the Calumet and Hecla Geological Staff at the Ann Arbor Meeting of the Society of Economic Geologists,[35a] the thesis was presented that leaching of hematite from the country rock had oxidized the sulphur of the ore solutions, giving rise to sulphates and the native copper. An imposing array of field evidence backed by painstaking microscopic and chemical work was offered in support of the hypothesis, and one cannot help but recognize the plausibility of their explanation of the origin of native copper. The strength of their arguments lends support to the application of the same idea to the origin of the Bristol chalcocite, except for the difference in degree of oxidation of the sulphur. And in a very small way the adequacy of the explanation for the Bristol ores is a humble contributory support to the process having operated to form the native copper of Michigan. At least it forms another small link in the occur-

[35a] December, 1922.

rence of somewhat similar ore deposits formed by similar processes.[35b]

The Bristol deposit might be considered as a half-way stage between deposits such as those of Michigan and Corocoro, Bolivia, where the oxidation of the sulphur has been so complete as to produce native copper, and ordinary copper deposits formed by magmatic waters where there has been no oxidizing action on the solutions. The Bristol deposit might have been a miniature Michigan deposit had the oxidation of the sulphur in the ore solutions not stopped half way.

An alternative explanation for the origin and mineral relations of the Bristol chalcocite is offered by simple physical chemical reactions without recourse to reduction of the copper by means of oxidation of the sulphur by ferric oxide, as explained above. The relative concentrations of iron and copper in the solution will determine whether deposition takes place of copper-iron sulphides or copper sulphides.[36] With high relative concentration of ferrous iron, deposition of the copper-iron sulphides will occur, but when the concentration of ferrous iron is lessened with respect to copper, deposition of copper sulphide will take place. Increase of the relative amount of copper in solution or decrease of the ferrous iron, whether by deposition of copper-iron sulphides or by influx of fresh solutions higher in copper, would lower the relative concentration of ferrous iron and yield conditions suitable for the deposition of copper sulphide. Also if influx of new solutions with higher ferrous iron concentration took place, as it probably would, there might again be deposition of iron-copper sulphides, until the relative concentration of iron to copper became so changed that copper sulphide in turn would again be deposited. In this may lie an explanation for over-

[35b] In the discussion which followed the presentation of this paper on the Bristol ores, at the Ann Arbor meeting of the Society of Economic Geologists, Professor Graton stated that in their investigation in Michigan they encountered chalcocite which they believe to be hypogene.

[36] The physical chemical ideas here expressed result from suggestions and discussions by my colleagues, Professor Harry W. Foote and Professor John Johnston, of the Department of Chemistry, Yale University.

lapping, corrosion, and intermingling of copper-iron sulphides and copper sulphide—features of such common recognition in most ore deposits.

Similarly the relative concentration of cupric to cuprous ions in solution would determine the presence of the cuprous sulphide—chalcocite, or the cupric sulphide—covellite.[37] As the insolubility of cuprous sulphide is so enormously greater than cupric sulphide, deposition of the cuprous sulphide would take place until the concentration of the cupric ion in solution became enormously greater than that of the cuprous ion—and only then would deposition of covellite take place. The rarity of covellite may thus be understood.

In the Bristol deposit the additions of ferrous iron would gradually grow less as leaching of the ferric oxide from the sandstone approached completion, so that toward the end of the metallizing period the relative concentration of ferrous iron would be so lowered that the copper would be deposited as the cuprous sulphide—chalcocite. It will be recalled that practically pure chalcocite was the last mineral deposited.

It is thus evident that there are two working hypotheses which would explain the occurrence of copper ores at Bristol. The one described above is based on known physical chemistry, and the other is highly suggestive, but as yet unproved chemically. The former must apply in the original formation of most copper deposits and in secondary enrichment of copper deposits, and may have been the most important factor in the origin of the Bristol deposit, but it does not explain, without additional elaboration, the presence of native copper and sulphates in such a deposit as at Cheshire, Conn. It is concluded that either hypothesis (or possibly both together) may explain the Bristol chalcocite, but in the meantime the oxidation of the sulphur by ferric oxide is considered as the more favored working hypothesis until the definite reaction of ferric oxide on sulphur solutions is determined in the laboratory.

[37] The ratio of cuprous to cupric copper in solution is governed by the ratio of ferrous to ferric iron, *i.e.* $\frac{Cu'}{Cu''} = K\frac{Fe''}{Fe'''}$. The constant K is as yet unknown.

Evidence from Wall-Rock Alteration.—The character of the wall-rock alteration or, more strictly speaking, the lack of it, shows that the mineralizing solutions lacked the virility to attack the wall-rock minerals. The varying degrees of intensity of chloritization, sericitization, and silicification, so universal an accompaniment of hydrothermal copper deposition, are wanting in the Bristol wall rocks. While it is true that the schists adjacent to the deposits contain considerable chlorite and sericite, it has been pointed out that this alteration is a characteristic of the formation as a whole and is a regional rather than a local alteration. The arkose of the hanging wall contains practically no sericite; the orthoclase and particularly the plagioclase feldspars in it are almost fresh, and plagioclase feldspar is a mineral very susceptible to alteration by mineralizing copper solutions. The metallizing solutions, then, because of their temperature or their chemical composition, or both, were unable to produce any appreciable wall-rock alteration and in this respect they stand in marked contrast to the solutions that have formed most copper deposits. What deductions, then, may be drawn from the nature of the Bristol wall-rock alterations to apply to the origin of the deposits?

The most outstanding inference is that the solutions which brought the copper were not highly heated, otherwise more intense wall-rock alteration would be expected. It is well known that in copper districts, as for example Butte, Montana,[38] the centers of mineralization are marked by higher temperature minerals and by intense wall-rock alteration, while the zones more remote from the centers of activity where lower temperatures are considered to have prevailed are characterized by minerals whose temperature of formation is lower, and by much less pronounced wall-rock alteration. The intensity of wall-rock alteration is, then, to a certain extent, a function of the temperature of the mineralizing solutions, although other factors as well must also play a part. By analogy, it is highly

[38] Sales, Reno H., "Ore Deposits at Butte, Mont.," *Amer. Inst. Min. Engrs. Trans.*, vol. 46, 1914, pp. 3–109.

suggestive that the Bristol deposit was formed by solutions that were not very hot.

Temperature of Solutions.—If it be granted that the Bristol chalcocite is of hypogene origin, then the occurrence of orthorhombic chalcocite crystals in the ore throws some light on the temperature of the solutions that deposited the chalcocite. The work of Posnjak, Allen, and Merwin[39] of the Geophysical Laboratory of the Carnegie Institute of Washington shows that chalcocite has two forms; an isometric form is produced above 91° C. which passes into an orthorhombic form below that temperature. At temperatures below 91° C. only the orthorhombic chalcocite is produced, and it is therefore the stable form under conditions pertaining near the earth's surface. They also found that chalcocite may contain covellite in solid solution and when the amount of dissolved covellite exceeds 8 per cent. there is no inversion, so that chalcocite containing over 8 per cent. covellite, and formed above 91° C., remains in the isometric form at normal temperatures.

The Bristol chalcocite is shown to have no dissolved covellite[40] so that inversion to the orthorhombic form would be expected had it originally been formed above 91° C. However, the Bristol crystals show no indication of ever having had an isometric form or structure. On the contrary, all of the crystals have clearly defined external orthorhombic forms. If the findings of the Geophysical Laboratory investigations be accepted as applying to nature, it would follow that the orthorhombic crystals at Bristol were formed at a temperature below 91° C. This conclusion must, however, be accepted with caution, since it is not known conclusively that all occurrences in nature of orthorhombic chalcocite are in agreement with the laboratory determination of the inversion temperature. Dr. H. E. Merwin states that although "many prompt inversions like that of chalcocite are known, no instance is on record of the low temper-

[39] Posnjak, E., E. T. Allen, and H. E. Merwin, "The Sulphides of Copper," ECON. GEOL., vol. 10, 1915. pp. 491–535.

[40] *Idem*, pp. 508–509.

ature form being grown above the inversion temperature or vice versa. Pressure might change the inversion temperature but the relatively slight pressures where cavities exist and crystals grow would probably have no significant effect. . . . Catalysis and variations in concentration of the solutions from which the crystals were growing would have no effect except as they affected the composition of the crystals themselves."[41] The Bristol chalcocite is remarkably pure.

In the case of the Bristol Mine there is nothing in the geology of the deposit to suggest that the ore may not have been formed at such a low temperature. In fact, the wall-rock alteration, the mineralogy, and the texture of the ore support the deduction of a low temperature of formation, though without affording specific temperature data. In view of the careful laboratory work in the determination of the inversion temperature of chalcocite, and the lack of contradictory evidence in the Bristol deposit, it seems most probable that the Bristol chalcocite was formed at a temperature less than 91° C

On the other hand, the occurrences of such minerals as quartz, barite, bornite, and chalcopyrite show the solutions were not ordinary cold waters, for the latter are not competent to transport and deposit minerals of this character; neither are they able to replace rock and gangue as these minerals have done. Hot solutions are implied, but not above a temperature of 91° C.

Source of Solutions.—It has already been concluded that solutions were the vehicle of transportation; that they were hypogene, that they were carbonated waters, and that they were hot but not above 91° C. As to the source of solutions that would meet these requirements, I think we must look to the nearby Triassic igneous activity. It cannot be fortuitous that the Bristol deposit and several other somewhat similar copper deposits in Connecticut, New Jersey, and Pennsylvania, all occur in the red Triassic rocks associated with trap or in the traps themselves (see page 136). The conclusion is inescapable that the igneous activity must have played an important rôle in the

[41] Private letter.

formation of the copper deposits. But, in the case of the Bristol deposit, the mineralizing solutions could hardly have come from the extrusive flows, for the ore lies considerably beneath the lowest of the three trap flows of the Connecticut Newark series. The volcanic reservoir that supplied the lavas must also have supplied the ore-carrying solutions and their metal content. The character of the solutions, as far as one is able to judge of them, is such as would be expected to accompany volcanism. Warm waters with carbon dioxide and other ingredients, such as were carried by the solutions that formed the Bristol ores, are usual after effects of volcanic activity,[42] and there is much to suggest that the Bristol ore-bearing solutions were of this type.

The ore-bearing solutions given off from a magmatic reservoir beneath would tend to travel upward, and the Bristol fault afforded a ready channel to conduct them to the site where mineral deposition took place. A temperature below 91° C. for such solutions is not inconsistent with this hypothesis, for even if the solutions possessed a higher temperature to start with, their journey through the rocks would produce the cooling necessary to bring them below 91° C.

Conclusions of Origin.—It is believed that in Triassic time, while the sedimentation of the Newark series of red arkosic sandstones was in progress, the magmatic reservoirs which gave off the trap intrusives and extrusives also emitted solutions charged with carbon dioxide, silica, calcium, sulphur, copper, silver, lead, zinc, and other ingredients. Part of these solutions were guided in their upward course by the channelway of the Bristol fault, and by the time they reached the site of the present ore deposit had a temperature somewhat less than 91° C. Their temperature and chemical composition prevented them from appreciably altering the wall rocks, but they were able to and did remove ferric oxide from the red sandstones.

The ferric oxide, as believed by Steinmann, and Singewald

[42] Clarke, F. W., "Data of Geochemistry," U. S. G. S. Bull. 616, 1916, pp. 225–284. Lindgren, W., "Mineral Deposits." 1919, pp. 91–114.

and Berry for the Corocoro deposits, and by Graton and his associates of the Calumet and Hecla Geological Department for the Lake Superior native copper, probably oxidized part of the sulphur of the solutions yielding ferrous iron and sulphates. The least soluble of the sulphates—barite—was precipitated, and any others that might have been formed were carried off in solution. Probably little or no sulphuric acid was generated. Not all of the sulphur was oxidized, probably because of its excess over the available ferric oxide, and therefore no native copper was formed. That the solutions were not originally deficient in sulphur is indicated by the abundance of sulphides.

The oxidation of the sulphur of the solutions was a continuous and gradual one, resulting in the deposition, first, of sulphides higher in sulphur, and later, of sulphides lower in sulphur. (Conversely the sequence of sulphides in decreasing order of their sulphur content is a substantiation of the oxidation of the sulphur by ferric oxide.) Also in the earlier stages of mineral deposition, there was enough sulphur even to satisfy some of the iron, and copper-iron sulphides resulted, while in the later stages of oxidation the sulphur was able to satisfy only the copper and that in a cuprous state

During the earlier part of the deposition of the sulphides, successive pulsations brought solutions of higher and lower degrees of oxidation so that a certain amount of overlapping of sulphides of higher and lower sulphur content occurred. But in the final stage of deposition when the diminishing sulphur content allowed only one atom of sulphur for every two of copper, there was practically no overlapping and relatively pure chalcocite crystals resulted.

The alternative hypothesis—namely, the control of the deposition of chalcocite and copper-iron sulphides by the relative concentrations in solution of copper and ferrous and ferric iron—may prove to have been the most important one in the formation of the ore, but for the present oxidation by ferric oxide is regarded with more favor.

SUMMARY.

1. The Bristol Mine at one time was the most important of several somewhat similar copper deposits of Triassic age scattered throughout the Newark Series of the Northeastern Atlantic States.

2. The deposit occupies part of a fault zone that separates the red arkosic sandstones from schists. The ore occurs as small irregular veins, and disseminated blebs and veinlets, in both sandstone and schist. Copper and silver were the metals won.

3. The ore consists chiefly of bornite and chalcocite, with subordinate chalcopyrite. Traces of galena, sphalerite, and pyrite are present. The gangue is quartz, calcite, barite, and siderite. Abundant crystals of quartz, calcite, and the sulphides of copper occur in drusy openings.

4. The copper sulphides are intimately intergrown with each other and with quartz and calcite, and are essentially contemporaneous in age. Orthorhombic crystals of chalcocite were formed last.

5. The chalcocite is concluded to be of hypogene origin.

6. The red sandstone surrounding the ore is bleached of its ferric oxide coloring matter, but the wall rocks are otherwise little altered.

7. The ferric oxide is believed to have oxidized part of the sulphur of the solutions and produced the hypogene cuprous sulphide—chalcocite. The sequence of earlier copper sulphides higher in sulphur and later sulphides lower in sulphur is considered to be due to a progressive oxidation of the sulphur in the metallizing solutions by ferric oxide. The oxidation did not proceed far enough to produce native copper.

8. Ferric oxide is considered to have played a similar rôle in the formation of the Bristol ore as in the case of the Corocoro deposits of Bolivia and the native copper deposits of the Lake Superior region. The chief difference is in the extent of the oxidation of the sulphur. The Bristol deposit, therefore, forms a connecting link between such native copper deposits and ordinary copper sulphide deposits.

9. A second working hypothesis based on known physical chemical reactions is considered, and while its importance in the formation of most copper deposits is pointed out and it is recognized that with further elaboration it may best explain the Bristol and analogous phenomena, it is for the present relegated to second place.

10. The mineralizing solutions are believed to have emanated from the volcanic reservoir that supplied the lavas, and to have possessed a temperature slightly less than 91° C.

I wish to acknowledge with grateful appreciation the helpful discussions regarding the Bristol deposit with my colleagues Professor John Johnston and Professor Harry W. Foote of the Department of Chemistry, and Professor Adolph Knopf and Professor William E. Ford of the Department of Geology.

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STUDY OF CAPILLARY RELATIONSHIPS OF OIL AND WATER.[1]

CHAS W. COOK.[2]

THE theories concerning the importance of capillarity in causing the accumulation of petroleum have been based largely upon theoretical grounds and to a lesser extent upon experimental evidence. The experiments have been of such a nature that conclusions had to be drawn from what might be called the end results rather than from direct observation of the action. Such questions as: How do the oil and water pass each other?, What is the minimum size of opening which will allow them to pass each other?, suggested the desirability of an attempt to make a direct study of the capillary relationships of oil and water while in contact.

Unless it is considered possible that water entering a shale from one side can force the oil out of the shale on the other side, any movement due to capillary force must result in an exchange of petroleum and water as between an oil shale and a water sand. Hence, these two substances must pass one another and the manner in which this is accomplished has a direct bearing upon the forces involved in the movement.

In order to study this movement a simple apparatus was made by taking five-inch lengths of 10-mm. glass tubing and drawing them out to capillary size in the middle, the ends of the tubes retaining their original diameter. The ends of the tubes were packed with mixtures of coarse sand and water, and fine sand and oil, and the action through the capillary tube was observed under the microscope. The apparatus is shown in Fig. 31*a*, in which, however, the exigencies of drawing have necessitated representing the capillary tube disproportionately large.

[1] Presented before the Society of Economic Geologists, Ann Arbor Meeting, December, 1922.

[2] The author is indebted to Messrs. R. H. Dott and L. M. Gould for assistance in the experimental work.

With the above-described apparatus, it was possible, in many instances, to observe the actual flow of both the oil and the water. The water flowed along the sides of the tube in one direction, while the oil passed in a solid column, through the middle of the tube, in the opposite direction (see Fig. 31*b*). In some tubes the actual movement was observable over a period of several weeks.

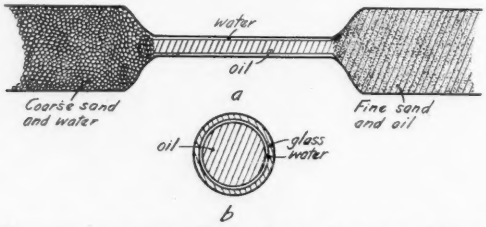

FIG. 31. *Diagram* (exaggerated) showing apparatus used in experiments.

A careful analysis of these facts shows that the assumptions which are commonly made the basis for the so-called capillary theory of the migration of petroleum are open to question, at least in part. To two possible modifications I wish especially to call attention. In all of the discussions of the subject which have come to my notice, the statement has been made or implied that capillary force and surface tension are synonymous and that the force exerted in producing the migration is equal to the difference between the surface tension of water and the surface tension of oil, subject to minor variations in each due to salts in solution, or temperature. Either it is necessary to modify this definition or else insist that capillary force alone is not competent to produce the movements accredited to it. Two molecular forces are active in causing the movement of liquids in capillary tubes, namely, either adhesion or cohesion, and surface tension. In the case of water, its rise in capillary tubes is due to the combined action of adhesion and surface tension. The result of the latter in attempting to decrease the surface area of the water, which has been increased by the force of adhesion, causes a move-

ment of a solid column of the liquid in the direction in which it has been drawn by adhesion.

If it is admitted that movements of petroleum may take place in which the petroleum is pushed ahead of the water and into unoccupied pore spaces, then the movements may occur as the result of capillary force alone, providing the definition of capillary force, as used in connection with the migration of petroleum, is modified to include the action of adhesion.

It is the writer's opinion, however, that if such movements do occur they are of relatively small importance in the accumulation of petroleum. In this connection, it is the movements in which an interchange of petroleum and water takes place that must be considered of prime importance. In this action, our experiments have shown, as already indicated, that the water moves along the side of the tube, itself forming a tube through which the oil passes in the opposite direction. An increase in the surface area of the water, therefore, occurs. To what shall this be ascribed? It has been pointed out that adhesion causes an extension and surface tension a contraction of the water surface. The present case cannot, however, be disposed of so simply. Instead of dealing with a two-phase system, we are here dealing with a three-phase system. The capillary opening through which the water is passing has its opposite walls composed of different materials, glass on one side and oil on the other. Between the glass and the water, adhesion is stronger than cohesion. Therefore the water creeps along the tube. Between the oil and the water, the cohesion of the water is greater than its adhesion for oil, so that the water tends to move in the opposite direction along the oil wall. The top surface of the water would tend to be concave on one side and convex on the other, and the effective force of surface tension would be the resultant of its attempts to cause movements in opposite directions. Hence, considering the water alone, the force producing its movement might be indicated thus:

$$ef = (a + ds) - c_1,$$

in which:

ef = effective force tending to cause movement of the water.
a = the adhesion of water for the glass.
ds = differential surface tension of water.
c_1 = the cohesion of water.

We have thus far dealt with only half of the picture. The oil is moving in a tube the walls of which are water. Since the cohesion in the oil is greater than its adhesion for the water, it assumes a convex surface and its surface tension tends to cause it to move in the opposite direction from that in which it actually has been observed to move in the experiment. Therefore, the capillary force of the oil, that is, cohesion plus surface tension, must act to oppose the movement of the oil. Taking these factors into consideration our equation becomes:

$$F = ef - (c_2 + s_2) \pm C,$$

or

$$F = [(a + ds) - c_1] - (c_2 + s_2) \pm C,$$

in which:

F = the force producing the migration of the oil.
c_2 = the cohesion of the oil.
s_2 = the surface tension of the oil.
C = correction due to moving walls.

If the above equation is a true statement of the molecular forces producing the movement of petroleum, two facts are readily apparent: (1) that the so-called capillary force producing the movement of petroleum is probably not equal to the difference in surface tension between oil and water and therefore cannot be calculated on that basis; and (2) that the adhesion of water for rock must be recognized as a possible important force in producing the migration of petroleum.

It seems strange that no authors on this general subject, so far as I am aware, have given due consideration to the effect of adhesion between water and rock. Some might appear to have done so were it not for their definition of capillary force al-

ready quoted. Ziegler[3] in discussing molecular attraction as a force producing the migration of petroleum states that three types may be considered, cohesion, adhesion, and surface tension. Adhesion he dismisses with the statement that it is probably of no great importance. He probably refers to the direct effect of the adhesion between oil and rock, but he neglects the possible indirect effect of the force of adhesion between water and rock. That adhesion alone may cause water to move to any distance in supercapillary openings is the statement of Van Hise.[4] If this is true, why should not the possibilities of adhesion be considered in the case of capillary openings?

Another fact observed during the progress of the experiments, which perhaps has a significance in connection with the migration of petroleum under the influence of molecular forces, was the effect of gas bubbles. Whenever an air bubble occurred originally in the capillary tube, no movement was discernible even after a period of three years. Also whenever a gas bubble (probably air) developed in a tube in which the actual movement had previously been observed, no further movement could be detected. It would seem, therefore, that the development of gas bubbles might, as Washburne[5] has pointed out, be quite effective in halting the migration of petroleum under the influence of molecular attraction.

The preliminary experiments seemed to indicate that the minimum size of opening, which will allow the interchange of oil and water to occur, is considerably larger than the minimum which will permit the capillary movement of either oil or water alone. Thus the experiments seemed to support McCoy's[6] contention as to the importance of faults in promoting the migration of petroleum by the force of molecular attraction. Later observations, however, indicate a possible modification of these conclusions. In fact, observations made upon tubes which

[3] Ziegler, Victor, ECONOMIC GEOLOGY, vol. 13, p. 339, 1920.
[4] Van Hise, C. R., U. S. G. S. Monograph XLVII., p. 151, 1904.
[5] Washburne, Chester W., *Trans. Am. Inst. Min. Eng.*, vol. 50, p 838, 1914.
[6] McCoy, Alex. W., *Jour. Geol.*, vol. XXVII., p. 261, 1919.

have been standing for a period of over three years suggest that the value of laboratory experiments as a basis for geological reasoning may be questioned, due to the inability of the investigator to give proper weight to the very important geological factor of time. This is evidenced by the fact that in tubes in which no actual movement was observable at any time, a transfer of oil could be observed to have taken place after periods ranging from six months to three years.

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GEOLOGICAL DISTRIBUTION OF THE IMPORTANT ORE DEPOSITS OF JAPAN.[1]

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INTRODUCTION.

SINCE the formation of the metallic deposits is the result of geologic processes, there is naturally an intimate relation between the geologic structure and the metallization of the area. Such a relation is striking in Japan, a fact familiar to the geologists and mineralogists of that country. However, little has been written on the subject, except in the Japanese language, which is not convenient for students of other countries. Hence, this paper was written, at the suggestion of Professor C. F. Tolman, in the hope that it may help American students to obtain a general idea concerning the geological features of the mineral deposits of Japan. It is not the result of a general study of the numerous ore deposits in Japan, nor a report of a new investigation of some of them, but it is merely a brief summary of my present knowledge of them.

As is well known, the Japanese Islands are arranged in three arcs, viz., the principal or Honshû arc in the center and the two smaller arcs of Ryûkyû and Kûrile at the southwest and the northeast ends respectively. The principal arc consists of four larger islands of Hokkaidô, Honshû, Shikoku and Kyûshû with many smaller ones. Geologically, the principal arc is further divided into two halves, *i.e.*, southwest and northeast Japan, and each half into the inner and outer zones, the whole arc being composed of four divisions.

These four divisions of the principal arc, as well as the two subordinate arcs, are characterized by geological structures and

[1] Throughout this paper the Korean Peninsula is not considered.

[2] In writing this paper, I am much indebted to Professor C. F. Tolman, who gave me many valuable suggestions, and also to Professor W. Lindgren, who read the manuscript.

mineralogical features quite different from each other. They will be stated in the following paragraphs.

ORE DEPOSITS OF SOUTHWESTERN JAPAN.

Zonal Division of Southwestern Japan.—From a geological standpoint,[3] southwest Japan is divided into an inner zone on the continental side and an outer zone on the oceanic side. However, from the standpoint of predominating rocks and ore deposits, it is more convenient to divide further the inner zone into two zones, *i.e.*, the narrow coastal region along the Japan Sea and the remaining portion, which lies between the coastal regions on both sides. Therefore, in this paper, southwest Japan is divided into three zones, namely, the outer, median, and inner zones, although the boundary lines between these three zones are different in nature from each other. The boundary between the outer and median zones is well marked by a line of a great dislocation, as was recently ascertained by H. Yabe,[4] whereas there is no sharp tectonic boundary between the median and inner zones. There is only a general difference of rock types and ore deposits. (Figs. 32 and 33.)

Ore Deposits of the Outer Zone.—The outer zone of southwest Japan is characterized by well-developed longitudinal ridges and valleys, by the regular parallel arrangement of various formations and by the great scarcity of igneous rocks. The predominant formations are crystalline schists, and Paleozoic and Mesozoic sediments; each formation being separated from the other often by longitudinal dislocation lines. The Tertiary formations are

[3] Concerning the goetectonics of Japan, prominent opinions have been proposed by several geologists, including E. Naumann, T. Harada, S. Suess, T. Ogawa, F. v. Richthofen, B. Kotô and H. Yabe. The principal points of opinions of these different authors, except that of Kotô, were recently summarized and criticized by H. Yabe, in his paper on "Problems Concerning the Geotectonics of the Japanese Islands" (Sci. Rep. Tôhoku Imp. Univ., ser. II., vol. IV., Pt. 2, 1917). Recent opinion of B. Kotô was expressed in his papers on "The Geomorphological Summary of Japan and Korea" (*Jour. Geol. Soc. Tokyô* vol. XXII., 1915) and on "The Volcanoes of Japan" (Same *Journal*, vol. XXIII., 1916).

[4] H. Yabe, Sci. Rep. Tôhoku Imp. Univ., ser. II., vol. IV., no. 1, 1915.

limited to small areas, and practically no volcanic rocks of the Cenozoic era are found. Granitic rocks are rare, and they are mostly of late Mesozoic or post-Cretaceous age.[5]

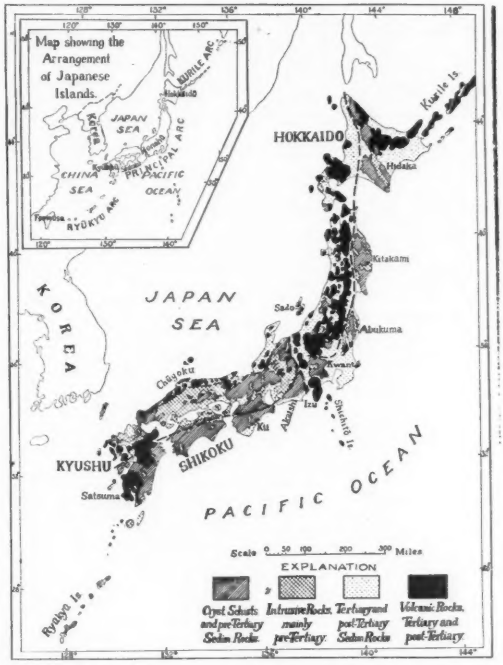

FIG. 32. Map showing general geology of Japan. The distinction between intrusive quartz-porphyry and effusive liparite and that between granite and gneiss, which is included in crystalline schists in this map, are uncertain.

From the mineralogical aspect also, this zone is distinguished by the zonal distribution of bedded replacement deposits, which

[5] For instance, the granite mass with porphyry facies, forming Mt. Ishizuchi in western Shikoku is most probably Tertiary in age, according to T. Ogawa, and the granite on Koshiki-jima is reported by T. Iki to be post-Cretaceous. Diorite also occurs in eastern Shikoku. It varies from quartz diorite to gabbro. The age of its intrusion is said to be post-Jurassic.

consist essentially of pyrite with some chalcopyrite and other minerals. The ore bodies are generally conformable with the country rocks, but locally they traverse the stratification planes of the latter—a fact which clearly indicates the epigenetic origin of these deposits. Nearly sixty mines of this type have been worked.[6] They are all arranged in a belt about 500 miles long and only 20 miles in maximum width. But their distribution is a little oblique to the trend of the geological formations. Thus, the western extremity of the belt is found in the Fukada and Itsuki mines, in formations of Mesozoic age. A little toward the east, the copper mines of Hibira and Makimine (Fig. 33, *6*) are located in the Paleozoic phyllites and slates.[8] Further east, numerous deposits of this type in the western Shikoku are mainly developed in crystalline schists of the Sambagawa Series.[9] The famous Besshi[10] Mine (Fig. 33, 5) and many other smaller mines, such as Takaura, Ôse, Kamizeki, Shirataki, and Nishinokawa, are mostly found in this formation, though some smaller mines are located in Paleozoic rocks. The Besshi Mine is one of the greatest copper mines in Japan. Its workings extend along what is practically a single deposit, more than 5,000 feet along the strike and over 4,000 feet down the dip. The deposit is enriched by chalcopyrite veins, formed by ascending solutions later than the deposition of the main mass of pyrite. The Higashiyama pyrite mine in the eastern Shikoku[11] and several pyritic deposits in the province of Kii and Yamato are arranged to the east in this same belt. Separated from these areas by some distance of barren district, the copper mines of Kune and Minenosawa in the central part of Honshû mark the east end of this belt.

Some portions of these deposits are believed to have been de-

[6] N. Ishikawa, *Jour. Geogr. Soc. Tokyô,* 1910 (in Japanese).[7]

[7] All the literature referred to in this paper is written in English, if not otherwise noted.

[8] T. Katô, *Jour. Geol. Soc. Tokyô,* vol. XXII., 1915.

[9] B. Kotô, *Jour. Sci. Coll. Imp. Univ. Tokyô,* vol. II., 1888.

[10] K. Arai, *Jour. Min. Soc. Japan,* 1911–1912 (in Japanese).
M. Kuhara, *Jour. Geol. Soc. Tokyô,* vol. XXI., 1914 (in Japanese).

[11] Y. Sagawa, *Bull. Geol. Surv. Japan,* vol. XXII., No. 1.

posited in open cavities in the sheared zone of the country rocks,[12] but mostly they were produced by replacement of schists, phyllite,

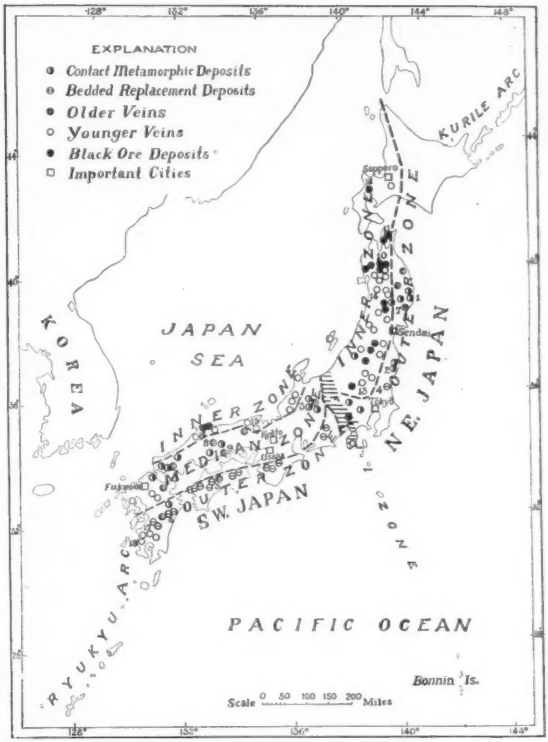

FIG. 33. Map showing the distribution of various types of ore deposits in Japan; numbers refer to mines which are examples of the type deposits characteristic of each district.

1. Kamaishi
2. Yakuki
3. Kamioka
4. Hitachi
5. Besshi
6. Makimine
7. Washinosu
8. Yoshioka
9. Obiye
10. Kosaka
11. Abeshiro
12. Kunitomi
13. Ashio
14. Arakawa
15. Ikuno
16. Omori
17. Yamagano
18. Kushikino

[12] Y. Sagawa, *op. cit.*

and clay-slate along the schistosity and stratification planes.[13] Replacement of limestone by this type of ores is rarely observed.[14] In almost every case, no igneous rock, except small masses of gabbro or serpentine, is observed near the deposits.

The geologic age of these ore deposits is not known definitely. Though they are mainly distributed in the crystalline schists and the Paleozoic formations, they may be much younger than the country rocks, some examples being found in the Mesozoic rocks.

Excluding this particular type of ores, localized in a special belt, the outer zone of southwest Japan contains few poor ore deposits. The antimony veins of the Ichinokawa Mine, famous for large crystals of stibnite, pyrrhotite-tin veins of the Mitate Mine,[15] small contact deposits near Kiura[16] and some minor veins of gold in Kii Province are rare instances.

No deposits of importance are known in the Tertiary or Quaternary formations in this region, except some minor amount of placer gold in the drainage of the Yoshino River in Shikoku and some smaller deposits of manganese ores.

Ore Deposits of the Median Zone.—The median zone of southwestern Japan presents a striking contrast to the outer zone in many geological and mineralogical features. Topographically it is a dissected plateau, with numerous transverse valleys.[17] Granitic intrusive rocks occur in extensive areas, and the Paleozoic and Mesozoic formations are found in detached areas, distributed without order.

This zone is characterized by a small number of districts where contact metamorphic deposits and older veins are relatively numerous. They are commonly developed at or near the contact between the granitic intrusives and the Paleozoic sediments. The deposits are seldom found entirely within the large masses of granitic rocks or in the districts exclusively underlain by sedi-

[13] T. Katô, *Jour. Geol. Soc. Tokyô,* vol. XXII., 1915, p. 12.
T. Hirabayashi, *Jour. Geol. Soc. Tokyô,* vol. XX., 1913 (in Japanese).
[14] M. Kuhara, *op. cit.*
[15] T. Katô, *Jour. Geol. Soc. Tokyô,* vol. XXI., 1914.
[16] N. Fukuchi, *Wada's Beiträge zur Mineralien von Japan,* No. 3. 1907.
[17] B. Kotô, Rept. Earthq. Invest. Comm. No. 63.

mentary rocks. They are usually developed around small intrusive masses or near the marginal parts of large batholiths. As a result the mining regions in this zone are found largely in three groups.

The western group contains numerous but small contact deposits of the Hananoyama[18] and Zomeki[19] districts, contact deposits of copper in the Sasagatani Mine, contact iron deposits of the Yoshiwara Mine, rich gold veins of the Basho Mine and chalcopyrite-tourmaline veins of the Yakuôji Mine,[20] all being clustered in the west end of Honshû and the northeast end of Kyushu.

The second group is represented by chalcopyrite veins of the Yoshioka and Obiye mines (Fig. 33, *8, 9*) and the pyritic deposits of the Yanahara Mine. The veins of the first two mines are developed in the contact aureole of small intrusive masses of porphyry and porphyrite in clay-slate and sandstone. They are frequently characterized by the development of amphibole and rarely by pyroxene, indicating the transitional stages to contact metamorphic deposits. Small contact deposits of Sasano, Bessho, etc., are also found near the Yoshioka Mine. The pyrite deposits of the Yanahara Mine are associated with diabasic masses from which the ores are believed by M. Kuhara[21] to have segregated. But this opinion seems to need further confirmation. Small chromite deposits of magmatic origin are also worked in serpentine masses not far from the district. They represent the only workable deposits of unquestionable magmatic origin in Japan. All of these deposits are located in the central part of Chyûgoku, and are separated from the first-mentioned group by large batholiths of granitic rocks.

The third group of mines in the median zone of southwest Japan is separated from the second by the mineralogically barren district around Ôsaka and Kyôto, and is located in the mountain-

[18] T. Katô, *Jour. Meiji Coll. Techn.*, vol. I., No. 1, 1916.

[19] R. Kimura, *Jour. Geol. Soc. Tokyô*, vol. XXII., 1915 (in Japanese).
N. Fukuchi, *Wada's Beiträge zur Mineralien von Japan*, No. 3, 1907.

[20] T. Katô, *Jour. Geol. Soc. Tokyô*, vol. XIX., 1912.

[21] M. Kuhara, *Jour. Geol. Soc. Tokyô*, vol. XXVII., 1920.

ous district of Hida in the central Honshû. This group contains the numerous deposits of lead and zinc ores in the Kamioka mines (Fig. 33, *3*) and the copper deposits of the Hiragane Mine. Almost every transitional stage is to be found from typical contact deposits, through replacement ore bodies, to fissure veins.

Though Paleozoic sedimentary rocks are frequent, bedded replacement deposits of pyrite are not found in this entire region, and although the Tertiary formations exist here and there, no deposit of black ore, to be described later, is known in this wide division of Japan.

The geologic age of the ore deposits in this region is not positively known. Usually they occur in Paleozoic rocks but occasionally in rocks of Mesozoic age. For instance, the contact deposits of Yanagigaura and Zōmeki[22] and the Shimonomoto veins in the Kamioka district occur in rocks of Jurassic age. In addition to this, the intrusive rocks which have intimate relation to the genesis of ore deposits are mostly post-Carboniferous, and mainly Mesozoic.[23] Therefore, the formation of contact deposits and older veins in this region seems to belong to certain stages of the late Paleozoic and Mesozoic periods.

Ore Deposits of the Inner Zone.—The narrow coastal region along the Japan Sea has many characteristics which distinguish it from the median zone, above described. This region, called the inner zone in this paper, contains several areas of depression, in which the sedimentary rocks of late Tertiary age and volcanic materials of late Tertiary to recent ages are accumulated. In these formations, ore deposits of quite different type from those of either the outer or median zone occur. The most important of these are filled fissures, which usually have the char-

[22] N. Fukuchi, *op. cit.*

[23] According to T. Suzuki, the granitic rocks in the west part of Chyugoku were intruded in at least two periods, one before the Lias and the other later. From the northern portion of Kyushu granitic rocks have been reported by T. Katô, probably Jurassic or Cretaceous age. The granite rocks in the Kamioka mining district are reported as pre-Jurassic, but the so-called basal conglomerate in the Shimonomoto Mine was recently proved to be nothing but severely sheared granodiorite along a reverse fault.

acteristic structures of deposits of the shallow zone. They contain no minerals, such as tourmaline, pyroxene, and amphibole, which are frequently observed in the older vein in the median zone. The famous silver-copper mines of Ikuno[24] (Fig. 33, *15*) and Omori (Fig. 33, *16*), copper mines of Ogoya and Yuzenji and gold-silver veins of Takeno and Togi belong to this group.

In addition, there are some small though remarkable deposits of black ore. This type of deposit is the most conspicuous one in the inner zone of northeast Japan.

The ore deposits in this region seem to be closely related to the volcanic activity, some of the important mines being located near the recent volcanoes. But they are not found in the recent lavas. They probably belong to the late Tertiary epoch.

ORE DEPOSITS OF NORTHEASTERN JAPAN.

Sub-division of Northeastern Japan.—Our present knowledge concerning the geotectonics of northeastern Japan is more scanty than that regarding southwestern Japan. Still a marked geologic contrast may be noted between the outer zone on the Pacific side and the inner zone on the side of the Japan Sea. Also the ore deposits of these two zones are quite different from each other, as will be described later. The outer zone of northeastern Japan, however, differs from the outer zone of southwestern Japan both geologically and in the predominating groups of metallic deposits. On the contrary, the similarity of the outer zone of the Northeast to the median zone of the Southwest is rather striking. Only a small area around the Hitachi Mine, composing a part of the outer zone of northeastern Japan, is characterized by the type of ore deposit which predominates almost exclusively in the outer zone of southwestern Japan. This area will be treated in this paper as a distinct district, though it is merely a part of the outer zone.

[24] The chalcopyrite-cassiterite veins of the Akenobi Mine are not included in this group, although the mine belongs to the Ikuno mines. These veins are developed in the Paleozoic rocks, at some distance from the major part of the Ikuno Mine. Geologically they belong to the median zone.

Ore Deposits of the Outer Zone.—The older formations of the outer zone of northeastern Japan are divided into the four individual segments of the Kwantô, Abukuma, Kitakami and Hidaka mountainlands. These four blocks are composed chiefly of gneiss, crystalline schists, and the Paleozoic and Mesozoic sedimentary rocks, together with notable amounts of intrusive rocks. They have the general character of a dissected plateau.[25] In this respect, these mountainlands resemble the inner zone of southwest Japan, although they do not constitute a continuous zone. They are separated from each other by wide areas of the Cenozoic formations and the present sea. Recently these blocks are believed by B. Kotô,[26] T. Ogawa[27] and Fred v. Richthofen[28] to be distinct horsts.

As a whole, the outer zone of northeastern Japan is rather poor in important metallic deposits, and especially the younger formations, which separate the mountain blocks above mentioned, are singularly free from any ore deposits, although these formations cover large areas. In general, they have undergone slight disturbances and are not associated with igneous masses. The four mountain blocks are characterized by a few contact metamorphic deposits of iron and copper, together with many gold quartz veins of minor importance. For instance, the Kamaishi Mine (Fig. 33, *1*) in the Kitakami district is the greatest iron deposit in Japan and the Yakuki Mine (Fig. 33, *2*) in the Abukuma district is one of the important copper deposits. They are both of contact metamorphic origin. The small Rokuromi Mine is a rarer example of a contact deposit which was worked for gold.

The gold quartz veins which have developed along the bedding planes of Paleozoic slate, or traverse the older igneous rocks are rather numerous in these districts, but they are usually low in gold content. In rare cases, such veins are locally very rich in

[25] B. Kotô, *Jour. Sci. Coll. Imp. Univ. Tokyô*, vol. V., 1893.

[26] B. Kotô, *Jour. Geol. Soc. Tokyô*, vol. XXII., 1915.

[27] T. Ogawa, Comp. Rendu de la Xme session de congres geologique international, 1907, p. 1273.

[28] Fred. v. Richthofen, "Geomorphologische Studien aus Ostasien, V. Gebirgskettungen in Japanischen Bogen," 1903.

gold, as was the case with the Washinosu Mine (Fig. 33, 7) once famous for large gold nuggets.

Both the contact deposits and the veins in the outer zone of northeastern Japan are found in the Paleozoic sedimentary rocks or in the igneous rocks intrusive into them. The age of intrusion is probably post-Carboniferous and in some cases it is clearly Mesozoic. Thus, for instance, some Triassic and lower-Cretaceous sedimentary rocks in the Kitakami district suffered contact metamorphism by the intrusion of granodiorite masses. The deposition of metals is likely to have close connection with the intrusion of these masses.

The District Surrounding the Hitachi Mine.—The ore deposits of the Hitachi Mine[29] (Fig. 33, 4) are quite different in nature from the above-mentioned deposits of the outer zone of northeast Japan, although this mine is located in the southern part of the Abukuma mountainland, which constitutes one of the fundamental blocks of this zone. The deposits of this mine are examples of large replacement bedded deposits, which are developed as several lenticular masses of pyrite, pyrrhotite, chalcopyrite, and zincblende, with small amounts of chlorite, quartz, and barite. The country rocks are amphibolite and other crystalline schists, which had been greatly metamorphosed before the deposition of ores by the intrusion of granodiorite and related igneous rocks.

In addition to the main deposits of the Hitachi Mine, small deposits of the same type are found in several places in the district around the mine. Some of these deposits are developed in the sedimentary rocks, which are known to be of Upper Carboniferous or Lower Permian age.

Ore Deposits of the Inner Zone.—The inner zone of northeast Japan is unique in that there is extensive development of younger Tertiary sediments, and accumulations upon them of volcanic materials. Smaller intrusive masses of andesitic or liparitic nature are also observed associated with these Tertiary sediments, and they are closely related to the ore deposition of the region. The ore deposits comprise two important types, widely distributed

[29] M. Watanabe, *Jour. Geol. Soc. Tokyô*, vol. XXVII., 1920 (in Japanese).

throughout the region, and they collectively constitute the most important source of metals in Japan.

The one of these important groups is the shallow vein type found in the liparitic and andesitic rocks and in the Tertiary sedimentary rocks around these masses. For example, in the great copper mine of Ashio (Fig. 33, *13*) are numerous chalcopyrite quartz veins, which run in two series of parallel systems. They traverse the eroded base of a funnel-shaped mass of plagioliparite, which probably filled a large explosion crater in the base rocks of Paleozoic age. Excellent crystals of various minerals are often found in druses in these veins. This fact indicates that these veins were formed by the filling of open cavities in a rather shallow zone. Similar types of chalcopyrite quartz veins occur in the Arakawa Mine (Fig. 33, *14*). They are developed along fault planes through Tertiary shales, tuffs and propylitized andesite, and are traversed by another set of later faults. Comb-structure is well developed in some veins of this mine.

This type of shallow vein in the inner zone of northeastern Japan includes tungsten-bearing gold-silver veins of the Nishizawa Mine; gold-silver mines of Sado, Innai, Handa, Takatama, etc.; copper mines of Ani, Osarizawa, and Furokura, besides Ashio and Arakawa; and the fluorite-bearing lead-zinc mine of Takada (formerly Hosokura) and many others. They are mostly developed in the eroded remnants of volcanoes or in Tertiary sedimentary rocks traversed by the shallow-seated intrusive rocks of that age. No deposit has been discovered in the Quaternary and Recent volcanoes, many of which are still active.

The other type of deposit in the inner zone of northeastern Japan is the so-called black ore bodies,[30] which commonly occur at or near the contact between Tertiary shales and tuffs and andesite or liparite,[31] usually intrusive into these sedimentaries. The

[30] T. Hirabayashi, "Report on the Investigation of the Black Ore Deposits," vols. I. and II. (in Japanese). T. Hirabayashi, *Wada's Beiträge zur Mineralien von Japan*, No. 4, 1912.

[31] The acidic volcanic rocks, associated with black ores, are usually varieties which contain phenocrysts of plagioclase, and they are often called plagioliparite.

typical black ore consists mainly of a mixture of galena and zinc-blende, with variable amounts of barite. Gypsum or anhydrite or both occasionally occur in place of barite. In addition to these minerals, black ore usually contains some chalcopyrite and pyrite. Where the lead and zinc minerals predominate, the ore assumes a typical black color and is commonly rich in silver; if the ore is rich in pyrite and chalcopyrite, it is yellow in color and its gold content is sometimes notable. According to such variation of composition, these ores are worked for gold, silver, lead and zinc. The oxidized product of black ore is often highly enriched in gold and silver.[32] As a result, this type of deposit is frequently first worked for gold and silver and then for copper. The deposits greatly vary in size and shape, but the general tendency is to diminish rapidly in size downward. Hence, many of the mines worked on this type of deposit are depleted after a rather short time. However, the discoveries of new deposits have been frequent enough to compensate for the decrease of product caused by the exhaustion of the older mines.

The largest example of the black ore deposits is in the Kosaka Mine (Fig. 33, *10*), where an irregular mass of black ore, 1,200 feet long, 400 feet wide and 250 feet thick, is surrounded by larger masses of pyritic and siliceous ores of low grade. The deposits of the Abeshiro (Fig. 33, *11*), Hanaoka, Kanô and Kunitomi (Fig. 33, *12*) are other large examples of this type of ore deposit, although some of them have been worked out.

The origin of the black ore is ascribed by most Japanese geologists to replacement near the surface.[33] R. Ôhashi,[34] however, recently proposed a theory that the ores were deposited from

[32] T. Katô, *Jour. Geol. Soc. Tokyô*, vol. XXV., 1918.

[33] T. Hirabayashi, Report on the Investigation on the Black Ore Deposits, vols. I. and II. (in Japanese).

T. Hirabayashi, *Wada's Beiträge zur Mineralien von Japan*, No. 4, 1912.

C. Iwasaki, *Jour. Geol. Soc. Tokyô*, vol. XXI., 1914 (in Japanese).

T. Katô, *Jour. Geol. Soc. Tokyô*, vol. XXII., 1915 (in Japanese).

[34] R. Ôhashi, *Jour. Geol. Soc. Tokyô*, vol. XXVI., 1919 (in Japanese).

Various opinions against this theory are also found in the same volume (all in Japanese).

submarine hot springs contemporaneously with the surrounding sedimentary rocks; but this opinion is strongly opposed by many others.

The geologic age of these deposits of black ore is probably late Tertiary. They are never found in Quaternary and Recent volcanic rocks, although deposition of barite is still going on in some hot springs of the black ore district.

THE BOUNDARY BETWEEN SOUTHWESTERN AND NORTHEASTERN JAPAN.

Whatever may be the geotectonic meaning of the much discussed boundary [35] zone between southwestern and northeastern Japan, it is clearly indicated by the rock formations and topography. All the older formations, composing the east end of southwestern Japan, are abruptly truncated along a line with a north northwest trend (Figs. 32 and 33). The parallel ridges and valleys of the Akaishi mountain system in the outer zone and the plateau of Hida in the inner zone are both cut by well-marked continuous slopes and a low undulatory surface underlain by Tertiary formations adjoins on the east side of this line. Upon this low land, which traverses the main island of Japan, large amounts of volcanic rocks of the Fuji zone occur and reach their highest point at the famous volcano of Fuji. The southern continuation of this zone is traced to the volcanic islands of the Shichitô group and then to the Bonnin Islands. This volcanic zone is characterized by great petrographical heterogeneity.

The ore deposits in this zone are neither abundant nor important. Small gold veins in the andesite and liparite of the Idzu Peninsula and a small black ore deposit of the Takara Mine are rather rare examples.

MINERALOGICAL ASPECTS OF THE KURILE AND RYÛKYÙ ARCS.

In the small arc of Kurile or Chishima, which consists essentially of volcanic islands, practically no metallic deposits have been found, although some of the volcanoes on these islands have

[35] H. Yabe, *op. cit.*

yielded sulphur. There is little prospect of discovering any important metallic deposit in the young volcanic rocks forming these islands.

The islands of Ryûkyû are also poor in ore deposits. Only a few small masses of pyritic bedded replacement deposits have been known in the clay-slate and phyllite of Ôshima and Kerama islands. However, the northern part of Formosa and the south end of Kyûshû are generally considered as belonging to this zone, and both of these districts are rich in gold veins, accompanied by disseminated ore. Numerous gold deposits of the Satsuma (Fig. 32) are developed along thin fissures in the older andesite composing wide lava plateaus, on which volcanic cones of younger andesite, free from metals, are found. A part of the gold is found disseminated in the altered andesite near the veins. The gold mines of Yamagano (Fig. 33, *17*), Serigano (Fig. 33, *18*), Ushio, Ôguchi, etc., are developed on this type of deposit. The gold veins of Zuihô and the gold-copper deposits of Kinkwaseki, both in northern Formosa, are also of this same type.

METALLOGENETIC DIVISION OF THE JAPANESE ISLANDS.

As has already been stated, there is a marked regularity in the distribution of important metallic deposits of Japan. In this connection, C. Iwasaki[36] divided the whole country into five metallogenetic provinces, namely, the Korean, Kitakami, Besshi, Kosaka and Satsuma provinces. Generally speaking, his division is proper, but he laid too much stress on the kinds of igneous rocks related to the ore deposits, and especially on the igneous rocks of the representative mines. In my opinion, it may be impossible to strictly divide any wide region into distinct metallogenetic provinces, sharply separated from each other. However, if it is convenient for generalization to divide the Japanese islands into such provinces, it is better to take into consideration all the geological and mineralogical features, as far as it is possible. Accordingly the several regions which have been sepa-

[36] C. Iwasaki, *Jour. Sci. Coll. Imp. Univ. Tokyo*, vol. XXXII., 1912.

rately described in the previous pages will be regarded as so many metallogenetic provinces. They are as follows:

	Region.		Representative Mines.	Proposed Name of Province.
Principal Arc.	Southwest Japan	Outer zone	Besshi, Makimine	Besshi Prov.
		Median zone	Yoshioka, Kamioka	Yoshioka Prov.
		Inner zone	Ikuno, Ômori	Ikuno Prov.
	Northeast Japan	A small part of outer zone	Hitachi	Hitachi Prov.
		Main part of outer zone	Kamaishi	Kamaishi Prov.
		Inner zone	Ashio, Kosaka	Kosaka Prov.[37]
Ryukyu Arc.			Yamagano, Kinkwaseki	Satsuma Prov.[38]
Kurile Arc.			Practically no mine	

When the provinces which are similar in geological and mineralogical aspects are grouped into one larger province, the whole country may be divided as follows:

Name of Province.	Characteristic Deposits.	Predominating Rocks.
Besshi-Hitachi	Bedded replacement deposits	Crystalline schists, Paleozoic and rarely Mesozoic sediments. (Igneous rocks, rarely well developed.)
Yoshioka-Kamioka	Contact deposits and older veins	Paleozoic and Mesozoic sediments, and acidic intrusive rocks.
Ikuno-Kosaka	Black ore deposits	Tertiary sediments with andesite and plagio-liparite.
Satsuma	Younger veins and disseminations	Andesite.

GEOLOGICAL AGE OF THE METALLIC DEPOSITS OF JAPAN.

The important deposits may be divided into at least two groups. Most of those in the Ikuno-Kosaka province are developed in late

[37] The Ashio mine is greater than the Kosaka mine in many respects. However, the latter is selected for the name of the province, because it is the best example of the black ore deposits, which are almost exclusively found in this province and are most characteristic of it.

[38] In Satsuma, there are several mines which do not differ much in character and in scale. Hence, the name of the district is preferable to that of any one mine to be adopted as the name of a metallogenetic province.

Tertiary rocks, and are often unconformably covered by volcanic flows of the Quaternary age. They are chiefly the products of the late Tertiary. All of the black ore deposits and younger veins belong to this type. The veins and disseminations in the Satsuma province are also probably of the same age.

The contact deposits, older veins and bedded replacement deposits in the other two provinces are exclusively developed in the pre-Tertiary rocks, ranging from unknown early Paleozoic to the later Mesozoic. The geologic age of these deposits is in most cases unknown. So far as it was ascertained, they seem to belong to certain periods later than the Carboniferous and more probably in the Mesozoic. But the lack of Mesozoic rocks in most of the mining districts, however, makes it impossible to determine the youngest limit of the ore deposition. Possibly the mineralizing epoch of these older metallic deposits in Japan may be further divided into two or more sub-epochs. But the available data for this purpose are as yet so scarce that any attempt to make such subdivision in age has to embrace much speculation; hence, it will be better left to future investigation.

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EDITORIAL

THE ART OF REVIEWING.

No one connected in any intimate way with the publication of a scientific periodical can fail to realize that while most of us enjoy reading a good review, very few of us care to write even a poor one. The older men, those whose ripe experience and tempered judgment best fit them for the task, are usually "too busy" and the younger men appear to feel rather generally that any attempt on their part to appraise critically the work of an older investigator borders closely on presumption. The consequence is that the department of reviews, which might be one of the most interesting and valuable sections of the magazine, is, as a rule, deficient both in the quantity and the quality of the material submitted to it for publication.

What, in brief, is the purpose of a review? The reply will depend somewhat upon the outlook of the person interrogated. For example, the publisher naturally desires that his book shall have a large sale and the author is likely to be sympathetic with this desire. The main purposes, however, so far as most of us are concerned, are briefly two—first, to enable the specialist in the subject with which the book deals to decide whether the work is one that he needs, and, second, to inform investigators in related branches as to what is being done outside of their particular fields. This second purpose might, on first thought, be considered as tending to curtail the actual distribution of the book reviewed. It probably, however, has the opposite effect; for an adequate review of a good book is likely to be widely read and to leave in many minds impressions that may later result in definite recommendations.

In addition to the main purposes of a review there are many subsidiary purposes, to some of which incidental reference will be made in what follows.

To be of value, a review should be authoritative, accurate, impartial, and frank. It is not enough to present a bald abstract. Abstracting might be called the mechanical part of reviewing. It demands patience and some skill, but neither constructive thought nor ability of a high order. The mere abstract has a very useful place in scientific work, but it is not properly a review, although it is too often made to pass for one. The capable reviewer not only tells in a general way what is in a book, but discusses the contents in discriminating and critical fashion, calling attention to the particularly significant, original, or admirable features of the work, pointing out errors or omissions, making suggestions for improvement, and contributing to our knowledge of the subject by the citation of illuminating comparisons or by the introduction of examples from his own studies or experience. Obviously it is better and far more agreeable to emphasize the good points of a book than to dwell upon its defects. Nevertheless, imperfections and inaccuracies should not be passed over. Calling attention to them is sometimes deprecated as "destructive" criticism, but the epithet is not entirely appropriate. The intent of such criticism is not to injure a particular author, but to maintain a reasonably high standard on the part of authors and publishers.

It sometimes happens that publishers with many excellent volumes to their credit are far too lax in their acceptance of new manuscripts. They omit having them read critically by experts or appear to consider that the responsibility can be placed on the author, if their contract with him is properly drawn. Thus a book issued by a reputable publishing house may be so poor and so misleading as to call for outspoken condemnation. If the reviewer is sure of his ground, the objectionable features of the work should be frankly and fearlessly exposed. The writer of the present editorial recalls an incident illustrative of the foregoing statement. He once reviewed rather severely a certain text-book that had been compiled in such a slipshod and inaccurate manner as to make it wholly unsuitable for the use of students. Some time afterwards a member of the publishing firm

called upon him and, much to his surprise, expressed appreciation of the review. It appeared that the manuscript had been accepted with misgivings, and that the publishers were to some extent committed to issue a companion volume by the same author. The review so fortified their position as to make it possible for them to decline publication of the second work, which presumably would have been no better than the first.

To the veterans of economic geology I venture only to suggest that the writing of an occasional review of important publications in their respective fields is a duty that they owe to their colleagues. Reviews such as they particularly are capable of writing should be real contributions to the literature of their science and would add greatly to the value of any periodical in which they appear. To the younger workers in geology I wish to make a more specific plea.

Modesty, notwithstanding the low esteem in which it is held in most commercial pursuits, is an engaging quality that few scientific men would willingly see disappear. There is no real reason, however, why a young geologist whose training is sound and whose work, so far as it has gone, has been thorough and conscientious should hesitate to review publications in whose subject he is particularly interested. True modesty will appear, not so much in the declining of the undertaking as in the manner of its performance. To review successfully will mean work, including probably some collateral reading. The advantages to the reviewer, however, are manifold. He will have critically read the book and digested whatever of value it may contain. He will have fixed the important matters in his mind by his effort to abstract and express the essential ideas presented. He will have gained practice and increased facility in arranging and expressing his thoughts. Finally, a carefully written and illuminating review will give him a certain well-earned standing with his colleagues, and, furthermore, what is also helpful in any scientific career, will make his name favorably known to many who might not otherwise have heard of him.

It is a common mistake to suppose that a review must neces-

sarily be short. If a book is important and the reviewer is well up to his work, a review may properly be ten or more pages in length. If, on the other hand, the book is very poor, but, nevertheless, one that cannot properly be wholly ignored, the more briefly the disagreeable business is disposed of, the better, provided that the disposition is effective.

In conclusion, I wish to urge upon the readers of ECONOMIC GEOLOGY the importance of maintaining an adequate department of reviews, in which every review will be of high character and embody something of the personality and knowledge of the reviewer. This can be done only if those who are interested in the journal will undertake individually to contribute to this result.

F. L. RANSOME.

DISCUSSION AND INFORMAL COMMUNICATIONS

DESCRIPTION OF CLASTIC SEDIMENTS.

Sir: Geologists, and more specifically, petroleum geologists, who are concerned with the accurate description of the lithology of sedimentary rocks will welcome Chester K. Wentworth's clear and concise paper entitled "A Scale of Grade and Class Terms for Clastic Sediments," published in the *Journal of Geology* for July–August, 1922 (Vol. XXX., pp. 377–392). In order to bring it to the attention of some who may not see the original article, I am contributing this discussion to ECONOMIC GEOLOGY.

The lack of agreement as to what constitutes "coarse," "medium," or "fine" and the general looseness of terminology in describing sedimentary rocks has been a great handicap to the advancement of that branch of geologic science. The "Grade Terms" on page 381 and the "Class Terms" on page 390 will be a boon alike to teachers, students, research workers, practicing geologists, mining and other engineers. I have vivid recollections of the difficulty of comprehending on the one hand, and of trying to teach on the other, such indefinite terms as it has been the custom to use with sediments. Every geologist who has to work with borehole records of sediments which, as is too often the case, are left to the drill runner to describe, will hope that the two tables mentioned above will be posted up in front of every driller from the Mackenzie Valley to the Gulf of Mexico. This grading and classification is so simple and easily comprehended that it will require no great technical proficiency in lithology to make use of it. Certainly if it did no more than to make the average driller realize that there is more to be said about the rocks they bring to the surface than the monotonous succession of unqualified "conglomerate," "sandstone," "shale," it would

serve a useful purpose. With proper attention to color and an intelligent application of the principles given in this paper, borehole records, and especially diamond drill records, will be of much greater value than is now the case to the geologist who cannot personally examine the cores.

Where there is so much that is excellent I hesitate the slightest criticism, but I wish that a more favorable consideration had been given to the term "grit." I was taught by the late Hugh Fletcher to use "grit" as a name for rocks intermediate between coarse sandstones and, as we used to say, "pea-conglomerates." That is I would use the term "grit" for what Mr. Wentworth calls a "granule conglomerate." There is undoubted need for a name for rocks of this grade; and I prefer "grit" because it is shorter, easily remembered, more expressive, and at present is considerably used in this connection. In place of "granule," "granule grain," and "granule conglomerate" in the table of Grade terms, I suggest "grit grain," "grit gravel," and "grit."

The term "silstone," though to some extent lacking in euphony, fills a useful place, and is unquestionably better than "sandy shale." I confess no great admiration for "claystone," however, and rather question the advisability of dropping the old and well-established name "shale," though admitting the force of the reasons for which it was rejected.

These are but minor criticisms, however. Mr. Wentworth has given us a consistently reasoned set of terms, chosen with careful judgment, and I shall be surprised if his grading and classification does not meet with widespread and cordial approbation.

J. D. MacKenzie.

Geological Survey of Canada,
Vancouver, B. C.

ORIGIN OF THE IRON FORMATION OF THE MESABI RANGE.

Sir: There are a few points in Mr. Gruner's able and interesting paper on the origin of sedimentary iron formations in the

September, 1922, number of ECONOMIC GEOLOGY that call for remark.

In dealing with rock decomposition in the tropics it is stated that the process "is extremely rapid and extends to great depth." The rate of decomposition of rocks in the tropics varies greatly depending on their position with relation to ground water level. Rock that is permanently above that level decomposes very slowly and, owing to the absence of frost, disintegrates much less rapidly than in colder climates. Professor Lacroix calls attention to the surprising freshness of various plutonic rocks in French Guiana that had been exposed to the action of subaërial agents for ages. Below water level, however, decomposition goes on much more rapidly and may extend to great depth. One striking characteristic of this decayed rock is that practically invariably it is light in color, iron having been almost entirely removed. The active decomposing agents in the water appear to be alkaline carbonates, carbonic acid and the products of decay of organic matter (usually called humic acid) and their potency appears to be increased greatly by the slightly higher temperature at which they act in the tropics than in temperate regions, There seems to be no doubt that humic acid is effective in removing iron from silicates and it also tends to prevent the precipitation of iron from solution, but only to a very limited extent. Laterizing water, which issues at the surface and carries iron in solution as ferrous bicarbonate, yields a copious precipitate of colloidal ferric hydroxide and, in spite of the presence of humic acid, only a mere trace of iron is retained. The rapidity of the process, as frequently observed by the writer, is surprising. Of the iron dissolved by ground water only a very small fraction is deposited in laterite; vastly the greater part drains away in rivers.

It is true that vegetation is often sparse or absent on laterite beds *whose growth is complete.* This is to be expected since such beds occur commonly on plateaus and in terrace form. Let those positions be examined, however, where laterite *is now forming* (usually low-lying, very gentle slopes) and vegetation will be found in abundance.

On page 453 the present writer is credited with the belief that iron is deposited in laterite during dry seasons. This is incorrect. The factor determining the precipitation of ferric hydroxide from laterizing solutions is oxygen. Laterite can develop only in situations where air can gain access, *i.e.*, where ground water level is near the surface. Since this level is higher during the wet than the dry season and is sometimes actually at the surface, it is evident that oxygen gains access most freely in the wet season and therefore it is then that ferric hydroxide is most freely deposited, not in the dry season when water has retreated underground and little oxygen can reach it. Seasonal fluctuations in water level are of much greater importance in laterization than is capillarity.

Laterization is a very slow process; the beds increase in thickness from above downward; the rate of growth decreases with the thickness and is usually very much slower than the rate of lowering of the mean ground water level due to denudation.

Mr. Gruner's opinion (expressed at the top of p. 454) that a layer of hard iron oxide near the surface could form only in countries where there is a really dry season does not accord with facts. Hard ferruginous laterite layers are found in Malaya where a rainless week is very unusual and in the dense African and South American forests where the ground is steaming wet in the driest of seasons.

The presence of water, instead of hindering, is essential to the dehydration of ferric hydroxide in surface layers such as laterite.

If ferric hydroxide is subjected to prolonged heating and kept continuously wet it loses all its water below 100°, but if it is allowed to dry, *e.g.*, by exposure to the sun, heating for months to even 200° will not completely dehydrate it—a red heat is necessary. Silica acts in a similar way. Amorphous silica dissolved in water under pressure and slowly cooled deposits anhydrous silica (as quartz) in the water, but, if cooled quickly, forms a gelatinous mass from which the water cannot be completely removed except by heating to about 500°.

J. Morrow Campbell.

Maymyo, Burma.

REVIEWS

An Introduction to Sedimentary Petrography. By HENRY B. MILNER. Pp. 125. Plates 16, figs. 6. Cloth, 12mo. Thos. Murby & Co., London. Price $2.00.

"This book has been designed to aid the miscroscopical analyst of loose detrital sediments, whether for purely academic or economic purposes. It treats particularly of the principles, practice, scope and limitations of correlation of sediments by means of 'heavy' mineral concentrates, a factor of proved geological importance, especially in modern oilfield development." (Preface.)

The main portion of the volume is devoted to the description of the optical and other physical properties by which the mineral character of sand and silt grains may be determined. One chapter deals with the treatment of samples of sediments preparatory to their study. Another discusses the principles of the correlation of sediments with the aid of their characteristic heavy components; and another describes briefly how the observation of the groups of associated grains may furnish hints as to the source of a deposit, and how the state of preservation of the material of the grains may throw light on paleogeographic problems. In a very brief way the author calls attention to some difficulties in the interpretation of the results of studies of well samples, and of samples collected from sediments deposited on an oscillating sea bottom.

The book gives no specific methods for determining the nature of detrital grains, nor does it give specific directions for isolating mineral particles. It is assumed that the reader is acquainted with the usual routine of petrographic methods. Nevertheless it is a convenient little manual for those interested in the study of mineral fragments. It is to be regretted that there is nowhere in it any reference to the use of indices of refraction as determinative criteria.

The volume concludes with a bibliography of 82 entries of articles dealing with the lithology of sediments. W. S. BAYLEY.

Geology of the Tertiary and Quaternary Periods in the Northwest Part of Peru. By T. O. BOSWORTH; with an account of the Palæontology by HENRY WOODS, T. WAYLAND VAUGHAN, J. A. CUSHMAN, and others. Macmillan and Company (London), 1922, 434 pages, 150 text figs., 26 plates of fossils.

This interesting and abundantly illustrated book, written in a clear and direct way, tells of the geology and the present rugged and desert

environment of an oil field wholly in Tertiary strata along the coast of northwest Peru. The region lies a little south of the equator at the foot of the Andes, being from 15 to 40 miles wide, about 150 miles long, and some 200 to 1,000 feet above the sea. Its present annual yield of petroleum is about 4 million barrels, though up to 1920 the total yield was 34 million. Three fourths of the present production is by the International Petroleum Company of Toronto. The large yield of oil is all the more remarkable when one notes that the geologic structure of the entire area resembles "a giant crush-breccia" because of the countless faults, and further that the irregularly shaped and tilted blocks range from less than one acre up to several square miles in area. There is no alignment of the blocks, the throw is as much as 5,000 feet, and while the strata are in the main clay shales, there is an abundance of sandstones in thin and very thick zones, many of which have oil. Of "under water" there is almost none, in fact, there is believed to be too little water for the best concentration of oil, but locally "upper water" is present in quantity sufficient to disperse what oil there is. The production so far averages about 2,250 barrels per acre, but it is held that eventually the yield will rise to 5,000 barrels. In spite of the extraordinary amount of faulting, the scarcity of "under water," and the supposition that "there is no evidence that oil comes up fault-cracks or fissures," there is this abundance of oil held in the circumscribed sands as if locked up in "cells." On the other hand, we are told that "The least successful wells are those located on the large fault lines. The more productive territory is that which is least broken." While the individual wells are as a rule small producers, many are long-lived and some have been pumping for twenty years.

The Tertiary strata are here enormously thick, certainly over 17,000 feet and possibly as much as 25,000 feet. They become coarser toward the Andes, and the base of the Tertiary is unknown. More than two thirds of the strata are of middle and early upper Eocene age (= upper Wilcox and Claiborne of Alabama, and Tejon and lower Meganos of California), and the remainder is Miocene. Innumerable pebble zones recur throughout the entire Tertiary, and being replete with molluscs, attest the shallowness of the waters which deposited them. The Tertiary is overlain by thin sheets of marine Pleistocene strata (5 to 250 feet thick); they are the sediments of seas that abraded their way at least three times across this zone of "giant crush-breccia" for distances ranging up to 20 miles. There are three prominent elevated marine terraces, making the elevated table-lands, the "tablazos" of the natives. These tablazos are "a monument to the efficacy of marine erosion" and the account of their making is one of the most interesting parts of the book.

The fossils in the pebble zones are exceedingly common, though their

variety is not great. The Eocene strata have yielded 85 species (70 are new) and the Miocene 12 (4 new). The book was written long before E. M. Spieker's paper, "The Paleontology of the Zorritos Formation of the North Peruvian Oil Field" (Johns Hopkins Univ. Studies in Geol., No. 3, 1922), and for this reason takes no note of it. The fossils of the Pleistocene are all of living species; some of the oysters are 10 inches long, while barnacles 6 inches long make whole beds. The few corals, restricted to the earlier Eocene, did not make reefs, though they are of reef-making kinds. The smallness of these molluscan faunas also contrasts decidedly with the present richness of that of Peru, which Dall says has about 800 forms.

The Andean geosyncline was folded into mountains toward the close of the Mesozoic, and the region was peneplained during the Cenozoic. During the Eocene the Pacific cut its way into the Andes, and the latter shed into this ocean during the Tertiary an immense mass of detritals, the base of which was warped and faulted something like 20,000 feet into the depths of the Pacific. While this subsidence was going on, a great fault developed to the east of the detritals, the "geofault" of Bosworth, and during the Pliocene, while the Andes were rising vertically to their present height, the eastern remaining portion of the Tertiary continental shelf was broken up into the "giant crush-breccia." At the same time, there also originated, along the western side of the present continental shelf, the "Pacific fault," which during the Pleistocene let down the outer margin of South America into the Pacific abyss about 20,000 feet. In keeping with this sinking during the Pleistocene, the remaining Tertiary mass was "moved upwards and downwards hundreds of feet again and again. The sea advanced and retreated many times, cutting its cliffs into the land 10 miles or 20 miles on each occasion" (p. 258).

The book should be read by all geologists, especially for the account of the tablazos and the correlated elevated terraces of the rivers, and for the interesting story of nature's work in this coastal desert.

CHARLES SCHUCHERT.

SOCIETY OF ECONOMIC GEOLOGISTS

THIS department has been established for the official communications of the Society of Economic Geologists whereby the affairs of the Society may be brought regularly to the attention of its members.

As previously announced, the Society will hold a meeting in New York, May 18 and 19, 1923. The technical sessions are to be held at the United Engineering Societies Building, 29 West 39th Street; on Friday night a smoker will be held and on Saturday night a dinner, both at the Harvard Club.

Invitations have been extended to the members of a number of technical societies to attend these meetings, also to the faculties and graduate students in the Departments of Geology of the various Universities near New York.

Will those who contemplate offering papers for this meeting kindly communicate at once with Professor Alan M. Bateman, Yale University, New Haven, Conn., giving title of paper, brief abstract, time desired for presentation, and whether it will be presented in person, by substitute, or by title.

Frederick G. Clapp was appointed chairman of the Committee on Arrangements and Program for the May meeting of the Society. As Mr. Clapp had to be away, Chester W. Washburn has been appointed in his place.

At the January 10th meeting of the Council and Executive Committee, J. Volney Lewis was appointed Treasurer and Mr. S. H. Ball was reappointed Secretary for 1923.

The Council of the Society will welcome an expression of opinion from members who do not attend the May meeting as to their reasons in not so doing, in order that the Council may hereafter be guided as to the date and place of the spring meetings.

Professor J. Volney Lewis was reappointed as delegate of the Society to the Council of the Geological Society of America, Professor James F. Kemp being the delegate of the Geological Society of America to the Council of the Society of Economic Geologists.

D. F. Hewett, of the U. S. Geological Survey of Washington, D. C., chairman of the Society's Committee on Bibliography, is arranging for the preparation and publication of the first complete bibliography to be brought under the auspices of the Society.

The Society announces that a gold medal has been established, this foundation being the gift of the first president of the Society, Dr. R. A. F. Penrose, Jr.

The medal will be given in recognition of unusually original work in the earth sciences. The recipient of the medal need not be a member of the Society of Economic Geologists, but if he has done any geologic or other work remarkable in the earth sciences, he may be awarded the medal regardless of whether or not he belongs to any Society. The first presentation may be made at any time, and under no circumstances will the second or succeeding presentations be made in less than three years. Beyond the limit specified the medal may be presented at any time that any geologist or worker in the earth sciences shall show the necessary merit. The granting of the medal will be decided by the elective officers and Council of the Society of Economic Geologists, consisting of the president and vice-president, together with the five members of the Council, creating in all a voting body of seven members, of which six shall constitute a deciding vote.

The medal bears on one side the two hemispheres, which is the insignia of the Society, the other side being reserved for the presentation inscription.

SCIENTIFIC NOTES AND NEWS

M. R. Campbell, of the U. S. Geological Survey, has been relieved at his request of his duties as chief of the coal section in order that he may devote more of his time to physiographic studies. W. T. Thom, Jr., has been designated as chief of the coal section.

Henry Louis is retiring at the end of the current session from the Chair of Mining in the University of Durham, Newcastle-upon-Tyne.

G. E. P. Smith, of the Arizona Agricultural Experiment Station, has returned from the Geological Survey to Tucson.

T. W. Vaughan has resumed charge of the West Indian Surveys in the absence of Mr. Woodring. He was recently elected president of the Washington Academy of Sciences.

C. A. Bonine has been appointed Professor of Geology in charge of the Department at the Pennsylvania State College.

W. W. Mein has established his office in the California Commercial Union Building, San Francisco.

J. F. Kemp left on February 24th for a month's trip to Porto Rico and the Virgin Islands, in connection with the scientific survey of these islands under the auspices of the New York Academy of Sciences.

C. F. Tolman, Jr., professor of economic geology at Stanford University, has gone to Mexico to examine mines.

H. E. Gregory, of Yale University, has gone to Honolulu to continue in charge of the investigations of the Bishop Museum in the Pacific, and will return next September.

Louis D. Huntoon has returned from the Porcupine gold area of Ontario, where he was engaged on professional work for about three weeks.

Bailey Willis sailed in January for Chile and Peru, to investigate the recent Chilean earthquake under the auspices of the Carnegie Institution of Washington.

F. W. DeWolf, State Geologist of Illinois, was in consultation with Survey geologists in Washington in February.

F. Arthur Johnson, R. V. Bassler, and N. W. Shiarella, formerly of the staff of Johnson, Huntley, and Somers, have opened an office under the name of Anchor Oil and Gas Company at Sheffield, Pennsylvania.

H. A. Buehler, State Geologist of Missouri, was a recent visitor in Washington.

E. K. Soper has returned to New York from Europe, where he has been for the past six months on professional business.

Douglas W. Johnson, of Columbia University, has been elected a foreign member of the Swedish Society for Anthropology and Geography.

W. C. Morse and P. F. Morse, Consulting Geologists, have completed sixteen weeks of field work on the bauxite deposits of northern Mississippi, which included detailed mapping and the sinking of one hundred and fifty test pits and drill holes.

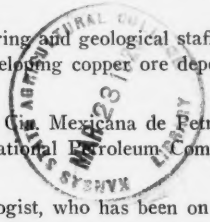
Eliot Blackwelder, who succeeded Dr. Bailey Willis in the chair of geology at Stanford University, was entertained by graduates of Stanford University at the Engineers Club of San Francisco.

H. E. George, of the U. S. Bureau of Mines, has been assigned to the Bartlesville station.

W. H. Blackburn, general manager of the Tonopah Mining Company, is to direct the reopening and exploration work in the Ajax Mine, Cripple Creek, Colorado.

M. E. de Margerie addressed the Washington Academy of Sciences and the Geological Society of Washington on January 24 on the subject of the Structure of the Alps.

E. Munoz Muluschka is on the engineering and geological staff of the Cia. Miniera de Aconcagua, which is developing copper ore deposits on the Rio Blanco near Santiago, Chile.



Thomas H. Kernan, formerly with the Cia. Mexicana de Petroleo El Aguila, is now geologist with the International Petroleum Company at Frontera, Tabasco, Mexico.

Alexander Deussen, consulting oil geologist, who has been on a business trip to Corsicana, has returned to Houston.

Frank L. Stillwell was a recent visitor at Yale, stopping over on his trip from London to Australia by way of the United States.

The Pan-Pacific Science Congress will open its meeting to be held in Australia at Melbourne, August 13 to August 22. This is to be followed by the Sydney meeting, August 23 to September 3. The tentative list of geological subjects to be discussed includes Coral Reefs, Glaciation, Structure of the Pacific Region, Carboniferous and Permian Problem, Correlation of Cretaceous and Cenozoic Sediments in Pacific, Mineral Resources, Vulcanology, Geological Surveys. The executive committee under the secretaryship of E. C. Andrews have made excellent plans for the visitors and have arranged that housing and accommodation will be free of expense to overseas colleagues and that free railroad passes will probably be secured for them for the same period.